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**FACULTY OF ELECTRICAL AND ELECTRONICS TECHNOLOGY AND  
INFORMATION AND COMMUNICATION TECHNOLOGY  
(DEPARTMENT OF ELECTRICAL AND ELECTRONICS  
TECHNOLOGY)**

**Performance Analysis of Particle Swarm Optimization (PSO) Tuned Smith  
Predictor Based Fractional Order PID Controller in Temperature Control of  
Electric Furnace**

MSc Thesis for the Partial Fulfillment of  
Master of Science in Electrical Automation and Control Technology Management

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January 2023  
Addis Ababa, Ethiopia



**Performance Analysis of Particle Swarm Optimization (PSO) Tuned Smith  
Predictor Based Fractional Order PID Controller in Temperature Control  
of Electric Furnace**

*A Thesis submitted to*

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FACULTY OF ELECTRICAL AND ELECTRONICS TECHNOLOGY  
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TECHNOLOGY)**

*In partial fulfillment for the Degree*

**MASTER OF SCIENCE *in* ELECTRICAL AUTOMATION AND CONTROL  
TECHNOLOGY MANAGEMENT**

*By,*

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## DECLARATION

I hereby declare that the work which is being presented in this thesis entitled” Performance Analysis of Particle Swarm Optimization (PSO) tuned Smith Predictor Based Fractional Order PID Controller in Temperature Control of Electric Furnace” is the original work of my own, has not been presented for a master’s thesis in this or other universities and all sources of materials used for this thesis work have been fully acknowledged.

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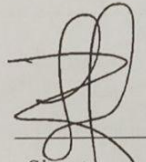
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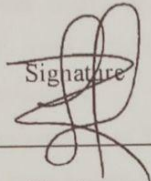
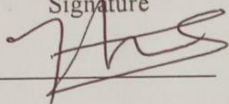

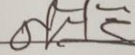
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## Abstract

The electrical furnace is a system that generates heat using electrical energy. By heating solid materials below their melting points, it is possible to shape the items into the required forms. Electric furnaces can be categorized as electric resistance furnaces, electric induction furnaces, and many other types depending on how the electrical energy is converted into heat. Electric furnaces are used in industries to braze, anneal, carburize, forge, galvanize, melt, harden, enamel, and temper metals, including copper, steel, iron, and magnesium alloys. Due to its simplicity in structure and design and ease of use, PID (Proportional + Integral + Derivative) controllers are often used in industries for temperature control. The choosing of values for the gain parameters is a challenging and time-consuming operation, whereas controlling using PID controller. Large peak overshoot and settling time is a frequent feature of PID controller responses. PID controllers are only appropriate for linear systems without time delays and mathematical models that are time invariant. However, the way an electric furnace's temperature control is non-linear and subject to time delays. Standard PID controllers do not perform adequately when used to control the temperature of the electric furnace. The Performance Analysis of Particle Swarm Optimization (PSO) tuned Smith Predictor based Fractional Order PID Controller in Temperature Control of Electric Furnace is proposed in this thesis. Finally, the performance of PSO tuned SPFOPID controller is compared with the SPFOPID controller, Fractional Order PID (FOPID) controller and conventional PID controller. The simulation result shows that, by using FOPID controller, the percentage overshoot is reduced from 71.1446% to 18.3924% and the settling time is also reduced from 19.9497second to 7.8006second. Also by using SPFOPID controller, the percentage overshoot is reduced from 18.3924% to 10.0851% and the settling time is also reduced from 7.8006second to 2.9906second. On the other hand by using PSO tuned SPFOPID controller, the percentage overshoot is reduced from 10.0851% to 0.4546% and the settling time is also reduced from 2.9906second to 1.7284second. This means, the PSO tuned SPFOPID controller shows less percentage overshoot (0.4546%) and faster settling time in the simulation results (1.7284sec). Generally, the PSO tuned SPFOPID controller improves the overall system performances as observed from the simulation results.

**Key words:** Electric heat furnace, Temperature, PID, FOPID, SPFOPID controller, PSO.

## Table of Contents

Acknowledgment.....	iii
Abstract.....	iv
Table of Contents .....	v
List of Figures .....	viii
List of Tables .....	ix
Abbreviations .....	x
CHAPTER ONE .....	1
INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objectives .....	2
1.2.1 General Objectives.....	2
1.2.2 Specific Objectives .....	2
1.3 Statement of problem .....	3
1.4 Significance of the Thesis .....	3
1.5 Scope and Limitation .....	3
1.6 Methodology of the Thesis .....	4
1.7 Organization of the Thesis.....	4
CHAPTER TWO.....	6
LITERATURE REVIEW .....	6
2.1 Introduction.....	6
2.2 Summary of Literature Review.....	17
CHAPTER THREE.....	18
MATHEMATICAL MODEL OF ELECTRIC HEAT FURNACE SYSTEM.....	18
3.1 Introduction.....	18

3.2 Modeling of electric heat furnace .....	18
3.3 Heat flow rate.....	20
3.3.1 Via Conduction.....	20
3.3.2 Via Convention and Radiation .....	20
CHAPTER FOUR .....	22
CONTROLLER DESIGN AND ITS TUNNING METHODS .....	22
4.1 Introduction.....	22
4.2 Proportional Integral Derivative (PID) Controller.....	22
4.3 Fractional Order PID Controller (FOPID) .....	24
4.4 Smith Predictor Based Fractional Order PID (SPFOPID) Controller.....	26
4.5 Manual tuning of PID controller.....	27
4.6 Conventional Tuning Methods for PID Controller .....	27
4.6.1 Ziegler-Nichols (Z-N) tuning .....	28
4.6.2 Calculation of PID controller using Z-N method for electric heat furnace system..	29
4.7 Tuning of FOPID controller .....	30
4.7.1 Calculation of FOPID controller for the electric heat furnace system .....	30
4.8 Tuning of SPFOPID controller .....	31
4.9 PSO tuned SPFOPID controller.....	32
4.9.1 Particle swarm optimization (PSO) .....	32
4.9.2 Global Best PSO.....	33
4.9.3 Parameters of PSO algorithms .....	35
4.9.4 Boundary value of parameters $K_p$ , $K_i$ , $K_d$ .....	35
4.9.5 Formulation of objective function .....	35
CHAPTER FIVE.....	36
SIMULATION RESULTS AND DISCUSSION .....	36

5.1 Introduction.....	36
5.2 Temperature control of electric heat furnace system .....	36
5.2.1 Open loop response of electric heat furnace system with time delay .....	36
5.3 Temperature control of electric furnace system using a conventional PID controller....	37
5.3.1 Discussion of Temperature control of an electric furnace system using a traditional PID controller.....	38
5.4 Temperature control of an electric furnace system using a FOPID controller .....	39
5.4.1 Discussion of Temperature control of an electric furnace system using a FOPID controller.....	40
5.5 Temperature control of an electric furnace system using a SPFOPID controller.....	41
5.5.1 Discussion of Temperature control of an electric furnace system using a SPFOPID controller.....	42
5.6 PSO-tuned SPFOPID controller temperature control for electric heat furnace system ..	43
5.6.1 Discussion of Temperature control of an electric furnace system using PSO tuned SPFOPID controller .....	45
5.7 Performance comparison of conventional PID, FOPID, SPFOPID controller and PSO tuned SPFOPID controller for the control of electric heat furnace .....	46
5.7.1 Discussion of Performance comparison of conventional PID, FOPID, SPFOPID controller and PSO tuned SPFOPID controller for the control of electric heat furnace ...	47
CHAPTER SIX .....	48
CONCLUSION AND FUTURE SCOPE .....	48
6.1 Conclusion .....	48
6.2 Recommendation for the future work .....	48
REFERENCES.....	49
APPENDIXES .....	53

## List of Figures

Figure 3. 1: schematic diagram of heating furnace [21][38].	18
Figure 4. 1: Block diagram of closed loop system [17].	22
Figure 4. 2: Block diagram of closed loop feedback control system with PID controller [7].	24
Figure 4. 3: Schematic Diagram of FOPID controller [35].	24
Figure 4. 4: Block diagram of closed loop feedback control system with FOPID controller .	25
Figure 4. 5: Block diagram of closed loop feedback control system of SPFOPID controller .	26
Figure 4. 6: the step response for using the ZN approach to choose L and T parameters [39].	28
Figure 4. 7: Flow chart on evolution of PSO algorithm	34
Figure 5. 1: Simulink diagram of open loop response of electric heat furnace system.	36
Figure 5. 2: Graphical of open loop response of electric heat furnace system	37
Figure 5. 3: Simulink diagram of electric heat furnace system using conventional PID controller	37
Figure 5. 4: Output response of the temperature management of an electric furnace system using a traditional PID controller	38
Figure 5. 5: Simulink diagram of the FOPID controller-based temperature management for electric heat furnace systems.	39
Figure 5. 6: Output response of temperature management of an electric furnace system using FOPID controller	40
Figure 5. 7: Simulink diagram of SPFOPID controller temperature management for electric heat furnace system	41
Figure 5. 8: Output response of temperature management of an electric furnace system using SPFOPID controller	42
Figure 5. 9: Simulink diagram of PSO-tuned SPFOPID controller temperature management for electric heat furnace system.	43
Figure 5. 10: Output response of temperature control of electric heat furnace system using PSO tuned SPFOPID	45
Figure 5. 11: Output response of temperature management of an electric furnace system using a traditional PID, FOPID controller, SPFOPID controller and PSO tuned SPFOPID.	47

## List of Tables

Table 4. 1: Different characteristics of the P, I, and D controllers.....	27
Table 4. 2: Z-N PID controller variables for the first order plus dead time model.....	29
Table 4. 3: lists the variables to utilize for the second set of tuning rules for plants with S-shaped step response when $0.1 < T/K < 50$ and $L < 0.5$ . ....	30
Table 4. 4: Parameters of PSO algorithms.....	35
Table 4. 5: Boundary value of parameters $K_p$ , $K_i$ , $K_d$ , $\lambda$ and $\mu$ .....	35
Table 5. 1: Performance measure, Time response specification and controller parameters of conventional PID controller	38
Table 5. 2: Performance measure, Time response specification and controller parameters of conventional PID controller and FOPID controller .....	39
Table 5. 3: Performance measure, Time response specification and controller parameters of FOPID controller and SPFOPID controller .....	41
Table 5. 4: Performance measure, Time response specification and controller parameters of the PSO tuned SPFOPID controller for ten runs.....	44
Table 5. 5: Best value of the Performance measure, Time response specification and controller parameters of PSO tuned SPFOPID controller .....	44
Table 5. 6: Performance measure, Time response specification and controller parameters of conventional PID controller, FOPID controller, SPFOPID controller and PSO tuned SPFOPID controller.....	46

## Abbreviations

$K_p$	Proportional gain
$K_i$	Integral gain
$K_d$	Derivative gain
$K_c$	Controller gain
$T_i$	Integral time
$T_d$	Derivative time
AGA	Adaptive Genetic Algorithm
IAE	Integral Absolute Error
PSO	Particle Swarm Optimization
PID	Proportional Integral Derivative
IMC	Internal Model Control
FOPID	Fractional Order Proportional Integral Derivative
IOPID	Integer Order Proportional Integral Derivative
SPFOPID	Smith Predictive Fractional Order Proportional Integral Derivative
SMC	Sliding Mode Control
ZN	Ziegler Nichols
LQG	Linear quadratic Gaussian
FPA	Flower Pollination Algorithm
MoFPA	Modified Flower Pollination Algorithm
PIDA	Proportional Integral Derivative Acceleration
AD	Analog to Digital
CHP	Combined Heat and Power
EMA	Electromagnetic Actuator
BP	Back Propagation
CFE	Continuous Fraction Expansion
FOPTD	First Order Plus Time Delay
$T_L$	Room/Lower temperature

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background

One of the most popular furnace types in use today is the electric furnace. Since more accurate temperature control is needed throughout various industrial production processes, it turns electrical energy into mechanical (heat) energy for heating. In industrial and technical processes, controlling temperature is an essential parameter. The physical properties of the processed material may change or decrease if the temperature is not correctly managed. As a result, it requires as much accurate and quick control as possible. Industries use a variety of controlling techniques; PID (proportional-integral derivative) control, IMC (internal model control), predictive control, and SMC (sliding mode control) are a few examples. But because of its simplicity, obvious functioning, and application, PID controllers are used by the majority of industries. The most well-known traditional PID tuning method is Cohen-coons, along with the Ziegler-Nichols (ZN) approach [1] [2].

Tuning is a difficult task for the researchers because of the non-linear properties of the system. In addition, system parameters might alter over time. Traditional PID controllers are linear and need experienced operators to change the coefficient, which takes time. Therefore, it requires the improvement of an optimum tuning method for the PID controller. The temperature needs to be properly and promptly managed because it is a major factor in today's industries. The low accuracy, lengthy rising time, and lengthy settling time of the controller are solved by the PSO tuned smith predictor (SP) based Fractional Order PID controller presented in this study. It offers precise and quick temperature control due to the considerable improvements in overshoot, settling time, and rising times [3]. The food and pharmaceutical sectors are greatly impacted by this exact and immediate regulation of temperature. We can prevent the change or degradation of the physical characteristics of the materials that are being processed since the temperature can be regulated accurately and instantaneously [1][2] [4].

## **1.2 Objectives**

### **1.2.1 General Objectives**

The general objective of this research is to analyze the performance of PSO tuned Smith Predictor based Fractional order PID controller in temperature control of electric furnace.

### **1.2.2 Specific Objectives**

- To simulate the mathematical model of electric heat furnace system using MATLAB Simulink software.
- To apply the conventional PID controller for the electric heat furnace system's temperature management.
- To apply the FOPID controller for the electric heat furnace system's temperature management.
- To apply the PSO algorithm for tuning of the parameters of the SPFOPID controller.
- To compare the performance of conventional PID controller, FOPID controller and PSO tuned SPFOPID controller graphical and numerical simulation results.
- Evaluate and interpret the result obtained from the simulation.

### **1.3 Statement of problem**

The electric furnace is one of the most widely used in the industry. Some process defects may be caused by the electric heat furnace's insufficient temperature regulation. Therefore the work temperature regulation is the key component in the electric heat furnace system, and it has an important effect on the process efficiency. There are many temperature controlling methods in the industries such as conventional PID controller, FOPID controller, SPFOPID controller and so on. Among those, most of the industries use PID controller. The PID controller, which is commonly used in the industry to control temperature, is not accurate, has high peak overshoot and long settling time, and is only appropriate for linear system without time delay time varying systems. However, regulating of the temperature of an electric furnace has the characteristics of non linearity and large time delay. So using conventional control methods, such as PID regulator, take longer time and high percentage overshoot to stabilize. Also using FOPID controller and SPFOPID controller, the performance of the temperature control of electric furnace is slightly improved but, still it takes long settling time and has high percentage overshoot to achieve the steady state, and can't meet the technical requirements properly. Therefore, efficient control and tuning methods are required to improve the performance of electric furnace temperature control systems.

### **1.4 Significance of the Thesis**

The presented thesis on temperature regulation for electric heat furnace systems might offer the following benefits.

- It increases the product quality.
- It safeguards against harm to the parts.
- It improves stability and performance.
- It reduces the risk of the system overheating.
- It increases productivity.

### **1.5 Scope and Limitation**

This thesis study mostly focuses on:

- To learn about application of optimization algorithms for tuning of controller parameters for obtaining better performance of the controller.
- To analyze an efficient method for tuning SPFOPID controller parameters for the electric heat furnace system's temperature management.

- To learn and getting exposure in design of advanced controller for the electric furnace system using MATLAB Simulation.

The finding of this thesis work is limited to the simulation study. It is not exactly applicable for real-time application because some assumptions and linearization procedures were considered to obtain a mathematical model of the electric heat furnace system.

## **1.6 Methodology of the Thesis**

The following methodology is used during conducting of this thesis work

- To acquire a broad sense of concept about the conventional and fractional order PID, and optimization algorithm tuned SPFOPID controller for the electric heat furnace system's temperature management, several related literatures works to the temperature control system have been reviewed.
- In this thesis work, the performance comparison of the difference controller for the electric furnace temperature control problem is carried out using MATLAB Simulink software environment.

## **1.7 Organization of the Thesis**

Generally there are six chapters in this thesis. The following is a summary of each chapter's content: - The introduction is covered in the first chapter of the thesis. The objective, problem statement, significance of the study, and range or scope of the study is all covered in this chapter.

A literature review is presented in Chapter 2. In this chapter, we look back at the history of the electric heat furnace system and examine its PID controller and FOPID controller.

The third Chapter is modeling of electric heat furnace system. This was explained in terms of how the thesis was arranged and the steps involved in finishing it or building a mathematical model for temperature of electric heat furnace.

The fourth Chapter is tuning methods of control system. This chapter discusses how to tune the parameters and optimize the PID controllers and FOPID controllers as well as PSO tuned SPFOPID controllers.

Discussion of the results of the MATLAB simulations is presented in Chapter 5. The output responses of the obtained results are analyzed. In this chapter, we analyze the results of using the PSO tuning algorithm to compare the efficiency of using a PID, FOPID, or SPFOPID controller.

The final section is titled "Conclusion and Future Work," and it consists of two subchapters. The chapter's overall conclusion is explained in view of the proposed controller for the control system. This chapter also includes some suggestions for improving the modified SPFOPID control of electric heat furnaces.

# CHAPTER TWO

## LITERATURE REVIEW

### 2.1 Introduction

Some related literature reviews of the temperature control of electric heat furnace systems are reviewed in this chapter. The study of the literature review helps in understanding the fundamental of the thesis.

One of the existing parameters that must be controlled in modern industry is temperature. The most critical requirements for this temperature control are accuracy and speed. The controller used to manage the furnace's temperature does not perform any better since conventional controls are not adequately adjusted. It has a high shooting value and a very long rise and settling time. A PID controller based on a genetic algorithm was introduced by M-M. M. Gani, M. S. Islam, and M. A. Ullah in 2019 to address the controller's low accuracy, long rising time, and long settling time. The algorithm estimates the PID controller's maximum number of gain parameters ( $K_p$ ,  $K_i$ , and  $K_d$ ) using this function. Due to considerable improvements in overshoot, settling time, and rising time, it provides accurate temperature control and operation. This quick and accurate temperature adjustment has a substantial influence on the food and pharmaceutical sectors[1].

The temperature controller is an integral part of the design of the control system for the furnace that uses crude oil as fuel. When dealing with interference, changes in load and system characteristics, and other issues, the typical PID controls used for temperature management fall short. Dou Zhenhai and Sun Lianyun (2012) developed the temperature controller to regulate adaptive fuzzy with variable slope, taking into account fluctuations in error rate and the connection between the rules factor and the error E. The system's reliability has been greatly enhanced. If you use it in the field, you will see positive results [2].

Some of the characteristics of the mathematical model for temperature control of a resistance-heated furnace described by J. X. Wang, J. F. Li, and D. Lu are non-linearity, strong inertia, time-variability, and pure delay (2012). Dynamically simulating a conventional PID control system for an industrial furnace was the inspiration behind the development of an adaptive genetic algorithm (AGA) based on these principles. Findings from both simulation and real-world use indicate that the proposed optimization method is both effective and

straightforward. This method of regulation has been shown to be more effective at maintaining a constant temperature in a resistance-heated furnace[3] .

X. Hu, Q. Zou, and H. Zou (2018) offered a method for controlling the temperature of an industrial electric furnace using fractional order predictive functional control. In order to improve the electric heating furnace's control performance, it is crucial to derive accurate modeling and controller design in light of complex components such as measurement noise, uncertainty, model/plant mismatches, and so on. When dealing with uncertain data, conventional control methods based on integer order models may fail to yield the expected control outcomes. The proposed controller has been implemented on an industrial heating furnace, and experimental testing shows that it is valid when compared to conventional integer model-based controllers [5].

The electric furnace's heating system is currently controlled by a PID controller due to its ease of use. Nonetheless, there is no conclusive answer to the problem of tuning and developing a versatile and effective PID controller. PID control from tuning using the Nelder-Mead technique was made available by V. Sinlapakun and W. Assawinchaichote (2015). If you follow the Nelder Mead map, you'll be able to access the PID controller's settings. Integral of Absolute Errors is used to determine how far off the desired size is from the actual size (IAE). When compared to other methods, such as Ziegler Nichols, Cohen-Coon, and Direct Synthesis, the PID-based design approach popularized by Nelder Mead is easier to implement and produces more robust results. The simulation result demonstrates that the proposed method improves upon the performance of the PID controller [4].

Smith's predictive control and the temperature control system for an electric furnace reported by J. Chang, D. Wang, and T. Li are evaluated and compared using a single-parameter PID control approach (2009). Single parameter PID control, which the simulation suggests has greater stability and resilience properties, is a practical and straightforward method for controlling a system with a significant time delay [6].

Chen, X., Chen, G., Yu, H., Jia, J., and Jia (2011) In order to account for the proposed non-linear and time-varying characteristics of an electric furnace, we developed a fuzzy PID controller and performed some simulations in MATLAB. After completing a property analysis, we compared the results from using a conventional PID controller versus a fuzzy PID controller. The results of the simulation show that compared to traditional PID control,

fuzzy PID control is more effective in terms of speed, stability, and immunity to interference [7].

Due to the high moment of inertia, lack of a time constant in the parameters, and time-varying nature of the system, conventional control methods take a long time to regulate the temperature of an electrical heating furnace. In other words, achieving the technical goals is difficult. In light of this, Ying-hong Duan introduces a refined Smith predictive fuzzy-PID composite control approach (2010). In this paper, we present a mathematical model for the electric heating furnace temperature control system, a new Smith predictive fuzzy PID controller, and a methodology for creating fuzzy control rules. By decreasing overshoot, shortening stabilization time, increasing control precision, and so on, simulation results show that the control system can be used effectively with an electric heating furnace machine [8].

The thermostat on a heating furnace is a finicky piece of equipment. The standard fuzzy controller often isn't able to guarantee that the system's regulating effect is preserved in its optimal condition at all times, as is the case with several truly complex control structures of heating furnace thermal process parameters. In an effort to find a solution, Xiao-hui Lil, Hui-yu Yang<sup>2</sup>, and Yan-jun Ren<sup>1</sup> (2009) proposed using a fuzzy control adjustment genetic algorithm to optimize parameters. This method improves the standard of control and regulation [9].

Fuzzy proportional integral derivation (PID) control is combined with expert judgment to regulate the temperature of a heating furnace, a problem first tackled by D. Shi, G. Gao, Z. Gao, and P. Xiao, who also developed the fuzzy PID control (2012). Since the PID settings are adjusted using the fuzzy reasoning method, this controller may learn to adapt to its environment. An expert's discretion can lessen the temperature change around the target value. If the error is larger than the set point, the temperature is regulated by the fuzzy PID. In all other cases, the decision to select the expert is automatic. A temperature-based PID expert-based temperature control system has the potential for faster response, smaller overshoot, and higher robustness than the traditional PID [10], as shown by simulation and experimental results.

Many different non-linear and extremely time-delayed processes make up the temperature control systems. Fractional-order modeling and related control approaches are said to be able to better regulate these processes. First-ever evaluation of the efficacy of fractional-order

control systems was performed using the linear quadratic Gaussian (LQG) evaluation benchmark by H. Li, R. Li, and F. Wu (2020). They did it by first thinking about how well the inputs and outputs worked together. Using an analytical technique to establish the LQG standard simplifies the final solution [11].

S. Garai, R. Dutta, S. Dey, S. Parui, and P. Chakrabarty reported on the creation and performance evaluation of a modified Ziegler-Nichols Tuning technique and internal model control method for a heat furnace temperature management system (2016). Numerous findings from this study show that IMC is an effective tuning method that outperforms more conventional approaches. The results of the process simulation show that the proposed strategy will work. It is demonstrated using a time domain specification that IMC-based systems offer less overshoot and faster settling times. Everything that was done for this project was done in MATLAB/Simulink. The simulation findings suggest that the IMC approach is useful for regulating dynamic processes, and a contrast between the IMC and the conventional approaches reveals that the IMC approach is more effective. The IMC tuning algorithm is optimal for determining the values of cascade controller gain that should be used for managing nonlinear processes like temperature, as suggested by the modified Ziegler-Nichols Tuning method [12].

To improve search performance, N. Pringsakul and D. Puangdownreong introduced the modified flower pollination algorithm (MoFPA) (FPA). To tell the difference between local and international pollinations, a random method is substituted for the actual FPA. We evaluate the proposed MoFPA against the baseline FPA and five benchmark optimization tasks. MoFPA is then used to optimize the electric furnace temperature control device's proportional-integral-derivative-accelerated (PIDA) controller architecture. There will be a comparison made between the machine responses obtained with the MoFPA-designed PIDA controller and those obtained with the MoFPA-designed PID controller. As a result, the proposed MoFPA achieves higher success rates in global best localization of five carefully selected benchmark optimization problems than the original FPA. As an added bonus, the PIDA controller developed by the proposed MoFPA may supply the advanced PID controller with highly appropriate monitoring and regulating responses for the electric furnace temperature control device [13].

Dr.K Babulu and D.Kranthi Kumar (2012) Proposed fuzzy logic based self adaptive PID controller in the application of temperature process control of electric furnace and this paper comprises the comparison of dynamic performance analysis of conventional PID, fuzzy based intelligent controller and fuzzy based self adaptive PID controller[14].

Inertia and lag are two characteristics resulting from the complexity of heat transmission in the heating furnace. Since the dynamic is unstable and the control precision is poor with a typical PID controller, it is unable to produce a satisfying result in the temperature control system for the heating furnace. This is especially detrimental to the system's ability to operate as efficiently as possible. Using the particle swarm optimization method, Peiguang Wang, Lian Zhang, and Xiaoping Zong (2015) created a fractional order PI-D controller and compared it to PID control. The simulation results show that the particle swarm optimization-based fractional order PI-D control performs better in terms of accuracy, convergence stability, and response times. Increased dynamic performance from fractional order PI-D controllers over conventional PID controllers benefits the quality assurance system greatly [15].

A Smith predictor-based fractional order PID (FOPID) controller is the focus of this work, and the primary contribution is an iterative optimization approach to its construction. Prajkta K. Bhamre suggests an extended dead time compensating smith predictor based management approach in this case (2016). FOPID controllers are more complicated to operate due to the addition of two new parameters: derivative order and integral order. FOMCON software and MATLAB/Simulink are used to create a controller for a connected tank system. Comparing FOPID, a fractional order controller based on the smith predictor, to SP-PID, a proportional, integral, and derivative controller, further demonstrates the efficacy of FOPID [16].

In this article, J. Paulusová and M. Dbravská discuss the fundamentals of control loop synthesis for linear continuous systems control using classical methods. Different types of continuous systems call for specific approaches to PID controller design. There is a comparison made between the two strategies' respective levels of command. Multiple controllers can be built, evaluated, and verified with the help of MATLAB and Simulink's PID controller design [17].

Rapid and accurate temperature regulation in an electric heating furnace is essential for manufacturing output. Shengyi Zhang and Zhihui XU (2017) use a C51 microcontroller, temperature sensors, an analog-to-digital (AD) conversion module, and a display module to create a temperature management system for an electric furnace [18]. The incremental PID algorithm is used to regulate the temperature of an electric heater.

YV Pavan Kumar, Arvapalli Rajesh, SadhuYugandhar, and Viswaraju Srikanth assess the efficacy of cascading PID controller systems in maintaining a constant temperature in a commercial heating furnace (2013). An ideal PID controller cannot be used to regulate non-linear processes like temperature. The full-system simulation results, performed in MATLAB/Simulink, suggest that the proposed cascaded PID design may lead to quick reaction times and robust dynamic performance [19].

R.Azarimi, A.K.Sedigh et al (2015) proposed an iterative optimization strategy for tuning the parameters of smith predictor based fractional order (SPFOPID) controller and the control scheme considered in this work is the standard smith predictor structure. There is also internal model is considered to be first order plus dead time (FOPDT) transfer function [20].

The output of the heater is controlled by the fractional order Proportional-Integral-Derivative (PID) controller, which was proposed by Amlan Basu and Mohanty (2017). The primary goal is to construct a fractional order PID utilizing a variety of tuning techniques, such as the Ziegler-Nichols and Cohen-Coon methods, and then compare and contrast their relative efficacies. Since it is important to understand the inner workings of the aforementioned methods before analyzing their results [21], this study also provides examples of the Ziegler-Nichols technique, the Cohen-Coon method, and the Nelder-Mead optimization algorithm.

M.S.Ghazizadeh looked into the mechanisms used to regulate the temperature of a batch tank in a glass manufacturing facility (2009). Significant amounts of heat energy are dissipated at the exhaust of a turbo-generator system Based on the results of the research; the authors suggest using a Neuro-PID controller for adaptive control. The simulation results show the effectiveness of the proposed controller in different modes of operation [22].

Two-degrees-of-freedom improvement Ziwei Li et al.(2020) propose a Smith predictive control method for commonplace industrial control systems. A well-known example is Smith predictive control, which was developed for pure lag systems. Internal model control, an extension of Smith predictive control, could reduce complexity in the controller design while effectively dealing with the time-delay problem. Based on the results of the two control algorithms, this study proposes a new control method with modified control parameters. For better control performance, the set-point tracking and disturbance rejection features can be developed as separate controllers thanks to the design concept's focus on decoupling them. The developed control strategy makes it simple to adjust its settings. The viability of the proposed strategy has been established through theoretical analysis and simulation comparison with other control techniques. Its superior performance in both set-point tracking and disturbance rejection is demonstrated by the results [23].

Maamar Betteyeb et al. (2017) established the first model-based analytical approach to developing a fractional order controller with a modified Smith predictor and a Smith predictor that is robust to changes in the process parameters. This method can be used to resolve systems with either fractional or integer order. Internal model control is used to create fractional order controllers based on the Bodes ideal transfer function. The simulation results show that the proposed method is effective for regulating linear stable systems of integer and fractional order with long time delays [24].

To stabilize a particular fractional dynamic system, Serdar Ethem Hamaamci has proposed the use of fractional-order PI and PID controllers (2014). As shown in [25], the global stability region for the fractional PID controller is displayed in  $(k_p, k_i, k_d)$ -space, while that for the fractional PI controller is shown in  $(k_p, k_i)$  plane).

Celaleddin Yeroglu et al. described in detail a new tuning method for fractional-order PID controllers with integer-order transfer functions (2012). Parameters of the controller such as its proportional gain  $K_p$ , integral gain  $K_i$ , derivative gain  $K_d$ , fractional order of the integrator  $\lambda$ , and fractional order of the differentiator  $\mu$  can be calculated using this method. Parameters for the fractional order controller can be generated using the proposed method, and empirical evidence shows that they outperform those for the integer order controller for a given system [26].

To tune the fractional order PID (FOPID) controller of the electromagnetic actuator (EMA) system for aero fin control (AFC), particle swarm optimization was proposed by V.K.kadiyala, R. K.Jatoth, and S.Pothalijah, et al., 2009. (PSO). The EMA is implemented with permanent magnet brush DC motors using constant current drivers. Using the non-linear model of the EMA-AFC system, which includes the DC motor's non-linearities, a FOPID position controller is developed using multiple soft computing approaches, such as PSO in SIMULINK, to guarantee that the system meets all design criteria. In this research, we introduce a PSO-based FOPID controller with PSO-based tuning. The design parameters that need to be optimized are the rise time, the peak time, and the percentage overshoot. Transient response and closed loop response using PSO-based FOPID tuning in the EMA-AFC system are demonstrated to be superior to those of conventional methods and an untuned system [27]. The goal of process control, which is a subfield of engineering, is to keep the output of a process within a certain bound. As a result of their ease of use and dependability, PID controllers are widely implemented for process tuning across a range of industries. PID controllers are typically tuned using the "Trial and Error" method, Ziegler Nichols, etc., which all use different PID algorithms. One major flaw of PID is that it cannot effectively deal with situations involving lengthy delay periods. M. Gnana Murugan and Mr. A. Senthilkumar (2011) suggested replacing the long delay time with the smith predictor with PID or Dead Time compensator, which works primarily on the closed loop and can be used to analyze open loop characteristics of the system. Based on the simulation results, it appears to perform better than the PID controller [28].

With respect to the smith predictor structure, Marzieh Safaei and Saeed Tavakoli came up with a quick and easy analytical technique to construct a fractional-order controller for time-delay integer-order systems (2017). Time-domain norms form the basis of the design process. Overshoot and settling time percentages are included in the design specs. Many tuning algorithms are designed to achieve these goals, and their basis is the ideal closed-loop transfer function [29].

M. Balaji and K. Porkumaran created dead-time compensation by applying a PID controller and a programmed logic controller (PLC) in real time to a heater-furnace system for temperature regulation (2016). Despite being effective at regulating the vast majority of operations, PID controllers have limitations when dealing with systems involving significant amounts of dead time. Using a PID controller with a dead-time compensator is recommended to lessen the effect of excessive dead time [30].

Fast and precise velocity control is crucial for the vehicles to achieve high control quality in their motion. The fractional order proportional integral derivative (FOPID) controller for speed regulation in micro intelligent vehicles (Mi-croIVs) was introduced by V.K.Kadiyala, R.K.Jatoth, and Pothalah (2017). Since selecting the parameters for FOPID controllers, which have two extra parameters, is more difficult than selecting the parameters for traditional integer order PID (IOPID) controllers, a better back propagation (BP) neural network is proposed and used in the parameters tuning of FOPID controllers. The implementation of the FOPID controller is difficult because the fractional calculus operators required by the controller cannot be used directly in numerical calculations. Fractional order calculus is transformed from the continuous to the discrete time domain by means of the Al-Alaoui generating functions and the continuous fraction expansion (CFE). Methods similar to those described in this study are used to demonstrate the efficacy and speed of the FOPID controller in controlling the motor velocity of MicroIVs. The experimental results show that the FOPID controller outperforms the IOPID controller in terms of control [31].

Particle swarm optimization is a method previously described by Russell Ebert and James Kennedy for maximizing nonlinear functions (2012). There is discussion and comparison of two paradigm implementations, one of which is a newly developed locally oriented paradigm. Applications such as neural network training and robot task learning are suggested, and benchmark tests of both paradigms are described. Particle swarm optimization is discussed in relation to artificial life and evolutionary computing [32].

The fuzzy PID temperature control system uses the Improved Particle Swarm Optimization (IPSO) algorithm after researchers analyzed the performance of the conventional PID control method, the Particle Swarm Optimization (PSO), and the fuzzy control algorithm. It was Qiang Wang who enhanced the particle swarm method (2022). The climate regulation apparatus is modeled in MATLAB. Results show that IPSO-based fuzzy PID temperature control systems perform better than conventional systems in terms of adjustment time, overshoot, and interference [33].

Amlan Basu and Sumit Mohanti introduced fractional-order elements to conventional PID controllers to enhance their performance (2017). The performance of the heating furnace is optimized by using multiple optimization strategies to determine the controller's tuning parameters ( $k_p$ ,  $k_i$ , and  $k_d$ ) and the vary integral's (and). The time response characteristics of the heating furnace plant and the various FOPID controllers developed using optimization methods are investigated while remaining in a closed loop. The study also presents the mathematical modeling of the heating furnace in integer order form, or a Laplace transform model [34].

Integer- and fractional-order PID controllers were developed by Amlan Basu and Sumit Mohanti (2017). Several tuning strategies are utilized during the design of PID controllers and fractional order PID (FOPID) controllers. Ziggler Nicholas, Cohencoon, Astrom-Hagglund (AMIGO), and Chien-Hrones-Reswick are just some of the methods used to calculate the proportional, derivative, and integral parameters of PID and FOPID. Nelder-Mead optimization is used to determine the correct values for the FOPID fractional order parameters. Each method's entire algorithm or tuning procedure has been described in detail. The designs, their step responses, and the features of the system are all discussed in detail [35].

Diwakar T.Korsane and VivekYadav proposed a method for effectively tuning the PID controller's parameters using a variety of PID tuning techniques (2004). For a first order plus time delay (FOPTD) form process model to be used with a proportional, integral, and differential (PID) controller, the controller gain ( $K_c$ ), integral time ( $T_i$ ), and derivative time ( $T_d$ ) must be calculated analytically. Specifically, a first-order time-delay system is the focus of this paper's analysis. Performance of PID tuning methods is analyzed and evaluated based on time response criteria [36].

FOMCON is MATLAB's new fractional-order modeling and control toolbox. It supplies a set of resources for researchers studying fractional-order control. Aleksei Tepljakov et al. provided an overview of the toolbox, discussed its motivation for development, and compared it to other fractional calculus toolboxes (2011). All the major parts of the FOMCON toolbox, along with some related mathematical ideas, are discussed. In total, you can choose from three different modules. The primary module is employed in the investigation of systems of fractional order. A fractional system can be identified with the help of either frequency or time domain data, thanks to the identification module. While the focus of the control module is on helping users design, tune, and optimize PID controllers for systems with a fractional order, it also provides some foundational support for developing lead-lag and compensators for systems with a fractional order. The resulting blockset in Simulink is then made available. It allows for the execution of more intricate modeling tasks [37].

In (2020), N.Abate proposed using model reference adaptive feed forward control to regulate the heat of an electric furnace during the glass tempering process [38].

In 2010, Duarte Valerio and Joses a da costa presented a review of tuning strategies for fractional PID, including analytical, numerical, and rule-based strategies [39].

Vicente Feliu-Batlle et al (2013) proposed a simple fractional order controller combined with a smith predictor scheme for controlling the temperature of steel slab reheating furnace. In these the fractional order integral controller combined with smith predictor controller is designed [40].

C.A.Monje B.M Vinagre et al. (2014) proposed the work to find out optimum settings for a fractional PID (FOPID) controller in order to fulfil five different design specifications for the closed loop system [41].

## **2.2 Summary of Literature Review**

Based on the information from the literature review, it was observed that the various control schemes are proposed in the literature. Still, the PID controllers are employed in most of the process industries. The tuning of the controller parameters is a difficult task in the case of a conventional controller and fractional order controller. The electric heat furnace system's temperature control is difficult because of having nonlinear characters and high delay time. The proper tuning of controller parameters is a critical problem in the PID controller. Besides, a comparison between the PID controllers with FOPID control approaches was also performed. Various optimization methods are described in the literature for the adjustment of controller parameters to solve this problem. It still needs some improvement in the area of controller tuning. Therefore, in this thesis work, the PSO tuned SPFOPID control system is proposed to obtain faster response and better control efficiency for the electric furnace system's temperature control.

# CHAPTER THREE

## MATHEMATICAL MODEL OF ELECTRIC HEAT FURNACE SYSTEM

### 3.1 Introduction

The materials and methods used to carry out the thesis are covered in this chapter. Digital computers and the matlab/simulink software are the materials used. They include modeling, designing, and analyzing. Each of them is covered in further detail in the following section.

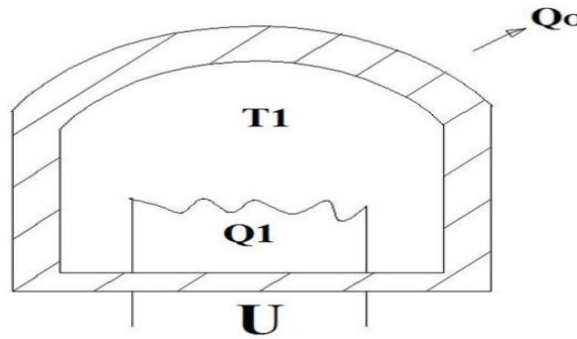


Figure 3.1: Schematic diagram of heating furnace [38].

Where  $U=H$  is amount of heat flow (power supply),  $T1= \theta1$  is the current temperature,  $Q1$  is input heat flow rate and  $Q0$  is output heat flow rate.

### 3.2 Modeling of electric heat furnace

In industrial procedures, the material is heated to the necessary temperature using an electric furnace. In an electric furnace, electrical energy is transformed into heat energy. Which it uses to heat the materials through conduction, convention, and radiation. Using the first order plus time delay equation, the electric furnace's temperature process is described as [1] [38].

$$G_p(s) = k \frac{e^{-Ds}}{Ts+1} \quad (3.1)$$

Where  $T$  is the time constant,  $D$  is the time delay, and  $k$  is the process gain. Assuming that the furnace's walls are perfectly heat-insulated and that are no external heat losses and the system heated by the furnace at  $150^\circ\text{C}$ . The equation for heat balance looks like this[34] [38]:

$$pcv \frac{d\theta}{dt} = H_2 - H_2 \quad (3.2)$$

Where:  $p$  is the material's density, expressed in tons per cubic meter.

$C$  is the material's specific heat, measured in Mcal/deg. ton,

$V$  is the volume of the furnace,  $m^3$ ,

$\theta$  is the temperature in zone,  $^{\circ}C$ ,

$H_1 = Q_1 \rho_1 C \theta_1$  is the amount heat flow with material  $Q_1$  Mcal/hour,

$Q_1$  is the flow rate input  $m^3$ /hour,

$H_2 = Q_2 \rho_2 C \theta_2$  is the amount heat flow with material  $Q_2$

Mcal/hour,  $Q_2$  is the flow rate output  $m^3$  /hour.

Considering the next assumption:

I.  $\theta_1(t) = \theta_2(t)$

II.  $Q_1 = Q_2 = Q$

Replacing the assumptions in equation (3.2) and

$$\rho CV \frac{d\theta}{dt} = H_1 - H_2$$

$$\rho CV \frac{d\theta(t)}{dt} = Q_1 \rho_1 C \theta_1(t) - Q_2 \rho_2 C \theta_2(t)$$

Where  $\theta_1(t) = \theta_2(t)$ ,  $Q_1 = Q_2 = Q$  and  $\rho_1 = \rho_2 = \rho$

$$V \frac{d\theta(t)}{dt} = Q \theta_1(t) - Q \theta(t)$$

$$V \frac{d\theta(t)}{dt} = Q (\theta_1(t) - \theta(t))$$

$$\frac{V}{Q} \frac{d\theta(t)}{dt} = \theta_1(t) - \theta(t)$$

$$\frac{V}{Q} \frac{d\theta(t)}{dt} + \theta(t) = \theta_1(t)$$

by taking Laplace transform gives:-

$$\frac{V}{Q} s \theta(s) + \theta(s) = \theta_1(s)$$

$$\theta(s) \left[ \frac{V}{Q} s + 1 \right] = \theta_1(s)$$

$$\frac{\theta(s)}{\theta_1(s)} = \frac{1}{\frac{V}{Q} s + 1} = \frac{1}{T s + 1} \quad (3.3)$$

Where  $T = \frac{V}{Q}$  time constant

Additionally, using  $H_1$  as the input, the transfer function is

$$\frac{\theta(s)}{H1(s)} = \frac{K}{Ts+1} \quad (3.4)$$

$K = \frac{1}{Q\rho C_p}$ , process gain (magnification value) and  $T = \frac{v}{Q}$ , time constant and delay

time  $D = \frac{L}{v}$  as explained in[38]

### 3.3 Heat flow rate

How to calculate the heat flow rate  $Q$  is as follows:

$$Q = \frac{H}{c_{pa}\rho_a(T_h-T_L)} \quad (3.5)$$

Where,

- $H$  is the material's heat flow amount (input power) in Mcal/hour,
- $Q$  is the heat transport rate by compressed air through an array of nozzles to a material surface (radiation and convection)
- $\rho_a$  is air density
- $c_{pa}$  is the air's specific heat, Mcal / deg.ton,
- $T_h$  is temperature heating
- $T_L$  lower temperature or room temperature

It is possible to calculate the required heat flow (input power)  $H$  as follows:

#### 3.3.1 Via Conduction

Rate of heat constant  $\propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$

$$H_{cond} = kA \frac{\nabla T}{\nabla X} \quad (3.6)$$

Where ( $K=0.003835\text{kw}/(\text{m}^\circ\text{C})$ ) is the material's thermal conductivity and ( $x=0.031\text{m}$ ) is material thickness and the furnace chamber's direct contact with the heater

$$H_{cond} = kA \frac{\nabla T}{\nabla X} = 0.003835 \frac{\text{kw}}{\text{m}^\circ\text{C}} * 4\text{m}^2 * \frac{120^\circ\text{C}}{0.031\text{m}} = 59380.65\text{watt} = 59.38\text{kw}$$

#### 3.3.2 Via Convection and Radiation

Heat transfer via radiation occurs in parallel with conduction (or convection, if there is bulk gas motion) when a gas, like air, surrounds a surface. This means that when the benefits of both methods of heat transfer are added together, the result is the total amount of heat transfer.

It is common practice to account for both convection and radiation by calculating a combined

heat transfer coefficient (hcombined).

Combining  $H_{conv\&radi}=h$  with  $A_s (T_s-T_\infty)$ , Where (h combined is the heat transfer coefficient through convection and radiation in  $w/m^2^\circ C$ , therefore take it as  $126.285 w/m^2^\circ C$ )

$T_s$  stands for surface temperature and ( $T_\infty = 30^\circ C$ ) for gas temperature.

The material's surface area that has to be heated is  $A_s$ .

Thus

$$H_{conv} = 60,616.8 \text{ watt} = 60.62 \text{ kw}$$

Therefore total amount of heat transfer is:

$$H_{total} = H_{cond} + H_{conv\&radi} \quad (3.7)$$

$$= 119997.45 \text{ w} \approx 120 \text{ kw}$$

Assumptions

- Length of furnace is chosen to be 2m
- volume of the furnace chamber is chosen to be  $4m^3$
- velocity of the material is chosen to be  $0.001 \text{ km/s}$
- the specific heat  $c_p = 2 \frac{\text{cal}}{\text{gram}^\circ C}$
- density  $\rho = 2.5 \text{ gram/cm}^3$

Electricity or electric power = 120 kw

Replacing in Eq. 3.6,  $Q = 0.2 \text{ m}^3/\text{s}$

In Eq. 3.5, substituting the values of  $Q$ ,  $V$ ,  $p$ , and  $C_p$  results in:

$$K=1, T=20\text{s and } D=0.2\text{s}$$

Thus the dynamic model of electric heat furnace is

$$G(s) = \frac{\theta(s)}{H(s)} = \frac{ke^{-Ds}}{Ts+1} = \frac{1e^{-0.2s}}{20s+1} \quad (3.8)$$

# CHAPTER FOUR

## CONTROLLER DESIGN AND ITS TUNNING METHODS

### 4.1 Introduction

This chapter presents the theoretical information about conventional PID controllers, Fractional Order PID (FOPID) controllers and Smith Predictor based Fractional Order PID (SPFOPID) controllers. Furthermore about particle swarm optimization algorithm is also presented in this chapter.

### 4.2 Proportional Integral Derivative (PID) Controller

A proportional-integral-derivate (PID) controller is a control loop feedback device that can be found in many different control systems. Using the PID control method, the combination of three types of corrective behavior is correctly applied to the error signal, which reflects how far or near the expected output is from the actual output. These three control activities are, as commonly understood, proportional, integral and derivative. Choosing the right combination of these three terms to produce the most effective process variable regulation for the problem under consideration, is the main point when tuning PID controllers.

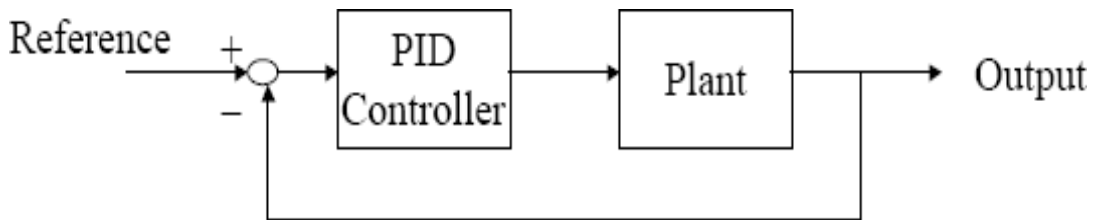


Figure 4.1: Block diagram of closed loop system [17].

Minimizing the error can be achieved by tuning the three parameters of the PID controller through the controller outputs. When it comes to performance and closed-loop response, picking the right controller parameter is crucial. In order to achieve the desired result, it is necessary to determine and employ the most suitable controller parameters. The least amount of overshoot and settling time in response to a step change in load or set point is a common requirement for optimal control. The controller makes an incremental change to a control variable, such as the position of a control valve, a damper, or the power supplied to a heating element, in an effort to minimize the error.

$$U(t)=K_p e(t)+K_i \int_0^t e(\tau)d\tau+K_d \frac{de(t)}{dt} \quad (4.1)$$

There, it represents the coefficients of the proportional, integral, and derivative terms, respectively, with all the non-negatives (sometimes defined by P, I, and D). The current error values are described by the proportional term. The proportional controller usually works steady state error because a non-zero error is needed to derive it. This is how the proportional gain is given:

$$K_{out}=K_p \quad (4.2)$$

The integral term describes the numbers of past errors and the collected error is then repeated with an integral gain and added to the control output. Integral is supplied by way of:

$$I_{out}=K_i \int_0^t e(\tau)d\tau \quad (4.3)$$

The term "derivative" refers to the error's future values depending on its current rate of change. Derivative of process error are calculated by determining the slope of the error over time and multiplying this rate of change with the derivative gain. The magnitude of the derivative term in the total control action is called the derivative gain,  $K_d$  and derivative term is given as follow

$$D_{out}=K_d \frac{de(t)}{dt} \quad (4.4)$$

By predicting system behavior, derivative action forecasts system stability and settling time. The PID algorithm's guarantee does not ensure system stability or even optimal control. Some applications may just need to use one or two terms to provide the appropriate system control. If there are no suitable control actions, the PID controller will be referred to as the PI, PD, P, or I controller. Due to the derivative action's sensitivity to measurement noise and the risk of the system failing to attain its target value in the absence of an integral term, PI controls are very common. Figure 4.2 illustrates the PID control method that acts as the position algorithm.

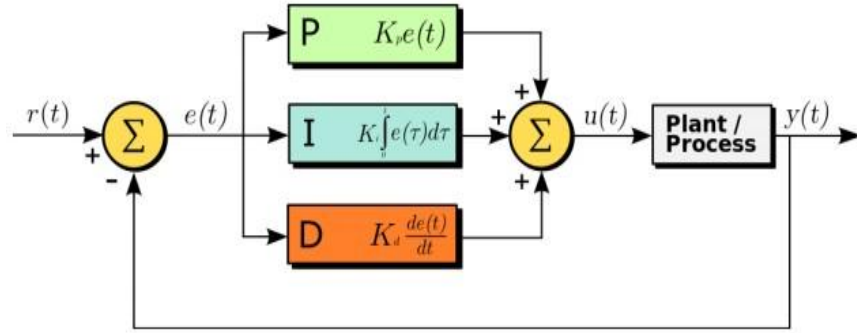


Figure 4.2: Block diagram of closed loop feedback control system with PID controller [7]. Where,  $u(t)$  and  $e(t)$  denotes the control and error signals of the system.  $K_p$ ,  $K_i$ , and  $K_d$  are the proportion, integral and derivative gain values. The corresponding PID controller transfer function ( $s$ ) is given as

$$G_c(s) = K_p \left( 1 + \frac{1}{\tau_i s} + \tau_d s \right) \quad (4.5)$$

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad (4.6)$$

### 4.3 Fractional Order PID Controller (FOPID)

FOPID controller, also known as the fractional-order  $PI^\lambda D^\mu$  controller and introduced by Podlubny [35], is a generalized version of the PID controller where the values of  $\lambda$  and  $\mu$  are between 0 and 1.

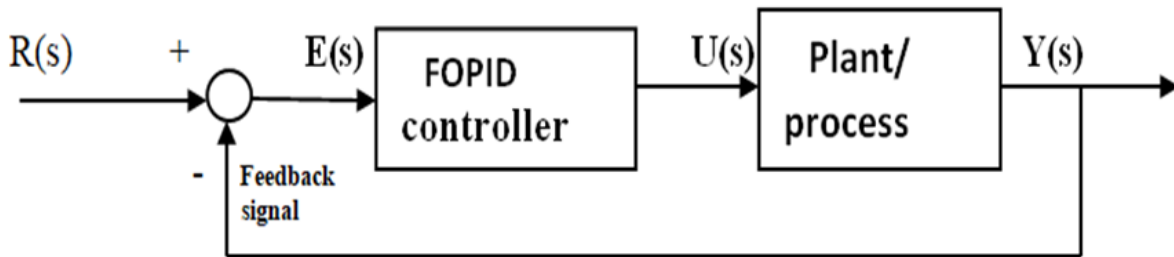


Figure 4.3: Schematic Diagram of FOPID controller [35].

The FOPID controller performs the same tasks as the PID controller, but it provides a better response since it has two more adjustable parameters. This increased flexibility in parameter tuning, compared to the PID controller, is crucial for increasing control accuracy. As a result, the electric furnace temperature control system uses a fractional-order  $PI^\lambda D^\mu$  controller [34] [35].

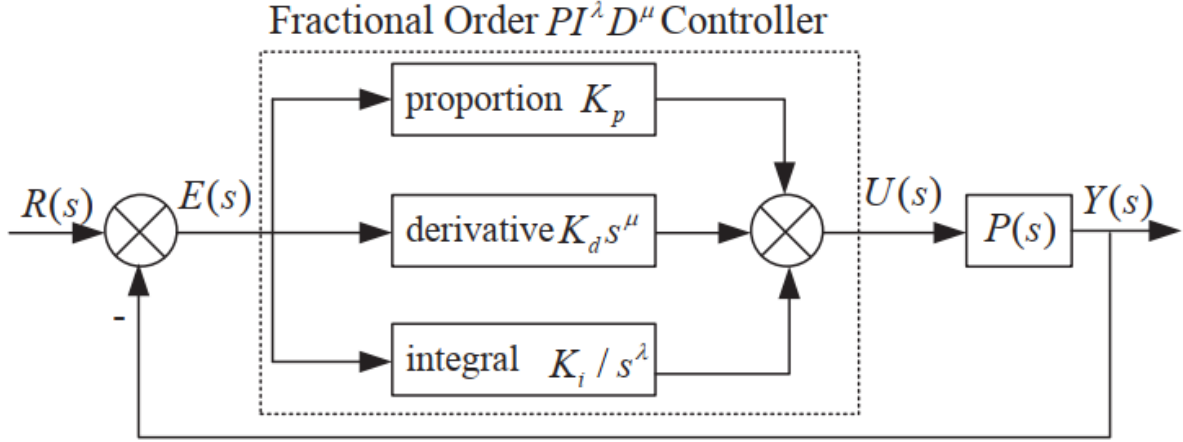


Figure 4.4: Block diagram of closed loop feedback control system with FOPID controller [31].

Equation 4.7 illustrates the differential equation of fractional order PID controller.

$$U(t) = k_p e(t) + k_i s^{-\lambda} e(t) + k_d s^{\mu} e(t) \quad (4.7)$$

Where,  $K_p$  is the gain of proportionality,  $K_i$  is the gain of integral,  $K_d$  is the gain of derivative and  $\lambda$  and  $\mu$  are differential-integral's order.

The controller transfer function is given by translating into the Laplace transform as follows:

$$G(s) = \frac{U(s)}{E(s)} = k_p + k_i s^{-\lambda} + k_d s^{\mu} \quad (4.8)$$

The traditional case for the PID controller is when  $\lambda = 1$  and  $\mu = 1$ , the conventional case for the PI controller is when  $\lambda = 1$  and  $\mu = 0$ , the conventional case for the PD controller is when  $\lambda = 0$  and  $\mu = 1$ , and the conventional case for the P controller is when both  $\lambda = 0$  and  $\mu = 0$ . All these classical types of PID controllers are the particular cases of the fractional order  $PI^{\lambda}D^{\mu}$  controller [25][26]. Thus, the  $PI^{\lambda}D^{\mu}$  controller can be considered as the generalization of the conventional PID controllers. It is clear that the fractional PID controller has a wider range of adjustment options than the traditional PID controller. As a result, the fractional-order controller's parameter performance is better than that of the traditional PID controller.

#### 4.4 Smith Predictor Based Fractional Order PID (SPFOPID) Controller.

The Smith Predictor is the most popular algorithm for dead-time compensation and one of the most popular compensating controllers. The proposed controller, which combines the Smith Predictor dead time compensator with the FOPID, keeps the PID's efficiency while eliminating dead time's effect on control performance. These long dead time processes benefit greatly from the following block diagram of the model-based controller's implementation. Each of its two time-critical components, the main controller and the inner loop are completely independent of one another [30].

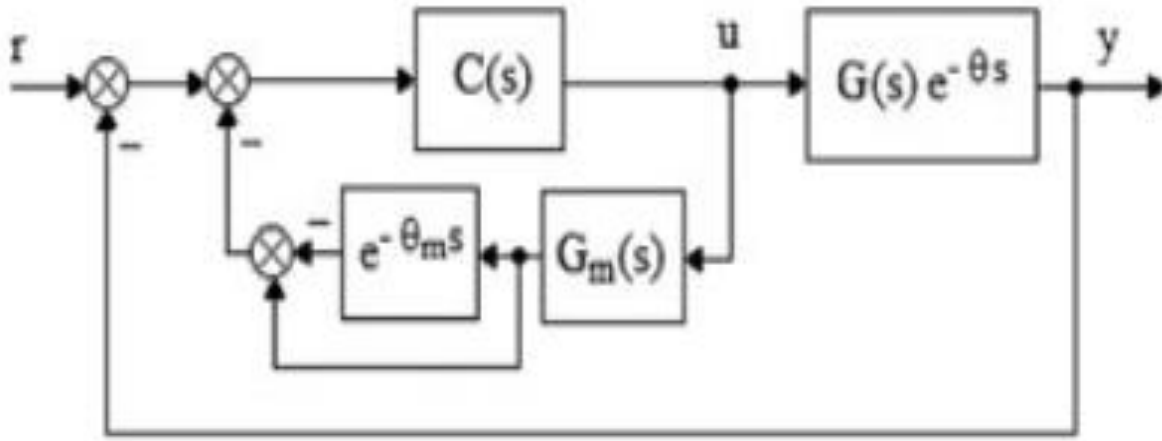


Figure 4.5: Block diagram of closed loop feedback control system of SPFOPID controller [24].

The structure contains a fractional order controller and an internal model which is considered as a first order plus dead time (FOPDT) transfer function where  $G(s)$  and  $G_m(s)$  are stable strictly proper rational functions characterizing the delay-free part of the plant and its model,  $\theta$  and  $\theta_m$  are positive constants standing for the time-delay for the plant and the model respectively.  $C(s)$  is the transfer function of the controller[24]. The inner loop works to eliminate the actual delayed output as well as to get the feedback of the predicted output to the controller. This makes it possible to design the controller  $C(s)$  assuming no time-delay in the control loop. The transfer function between the setpoint  $r$  and the output  $y$  of the closed-loop system is given as follow.

$$G_c(s) = \frac{C(s)G(s)e^{-\theta s}}{1 + C(s)[G_m(s) + G(s)e^{-\theta s} - G_m(s)e^{-\theta_m s}]} \quad (4.9)$$

In the perfect case where  $G_m(s) = G(s)$  and  $\theta_m = \theta$ , (4.9) reduces to

$$G_c(s) = \frac{C(s)G_m(s)}{1+C(s)G_m(s)} e^{-\theta s} \quad (4.10)$$

Due to the absence of the time delay in the characteristic equation of the perfect closed-loop, the controller  $C(s)$  can be designed with respect to the time-delay free part of the model regardless of the troublesome time-delay, and this will greatly reduce the design complexity of controller  $G_c(s)$ . This is also known as the time-delay compensation principle of Smith predictive control [23].

#### 4.5 Manual tuning of PID controller

Setting all gains to zero at the beginning is a way to manually tune the online system.  $K_p$  should be increased until the output is continuously oscillating. Then reduce  $K_p$  by roughly half to get a response with a quarter-amplitude decay. Then, keeping in mind that too high  $K_p$  can result in instability, increase  $K_i$  to decrease the P term offset for the process for a specific duration. When the oscillation is decreased and the system reaches the Setpoint quickly enough, raise  $K_d$  as needed [36].

Generally, the procedures for tuning of PID controller are:-

- 1<sup>st</sup>: Determine what needs to be improved by obtaining an open loop response
- 2<sup>nd</sup>: To improve the rise time, add the proportional control
- 3<sup>rd</sup>: Add the derivative control to enhance the overshoot
- 4<sup>th</sup>: Add an integral control to eliminate the steady state error
- 5<sup>th</sup>: Adjust each of  $K_p$ ,  $K_i$  and  $K_d$  until you get the desired overall response.

Table 4.1 shows the properties of the proportional (P), integral (I), and derivative (D) components of PID controller.

Table 4. 1: Different characteristics of the P, I, and D controllers.

PID gains	Rise Time	Overshoot	Settling Time	S-S error
Increasing $K_p$	Decrease	Increase	Small Increase	Decrease
Increasing $K_i$	Small Decrease	Increase	Increase	Large Decrease
Increasing $K_d$	Small Decrease	Decrease	Decrease	Small change

#### 4.6 Conventional Tuning Methods for PID Controller

The process of selecting the controller parameters ( $K_p$ ,  $K_i$ , and  $K_d$ ) for the feedback controller is known as controller tuning. The Ziegler-Nichols method of conventional tuning

is used in this thesis work to find PID controller parameters among other tuning methods used in traditional PID tuning technique [36].

#### 4.6.1 Ziegler-Nichols (Z-N) tuning

The most popular methods in process control for finding out PID controller parameters are Ziegler-Nichols design methods. Although these techniques introduced in the 1940s, these approaches are still commonly utilized today. The step response technique is built on top of an open-loop step response test of the process.  $L$  and  $T$  are two parameters that define the process' unit step response, which is why the process has to be stable in order to function properly. When inflexion occurs, where the step response's slope has its maximum value, these are calculated by drawing a tangent line [36][39].

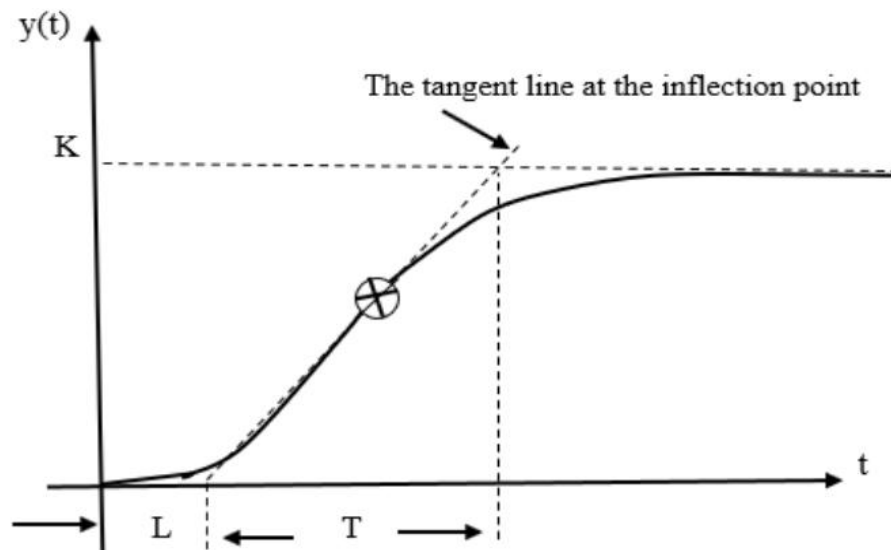


Figure 4.6: the step response for using the ZN approach to choose  $L$  and  $T$  parameters [39].

The process parameters, as illustrated in Figure 4.6, are obtained from tangent and coordinate axes at their intersections and are utilized to determine the controller settings. We may use the values of delay time  $D=0.2$ , time constant  $T=20$ , and gain  $K=1$  to calculate the values of  $K_p$ ,  $K_i$ , and  $K_d$  using various tuning relationships since our process model is first order plus dead time, as mentioned in chapter three. Table 4.2 displays the PID controller parameters derived from the Ziegler-Nichols approach.

Table 4. 2: Z-N PID controller variables for the first order plus dead time model

Controller	$K_c$	$\tau_i$	$\tau_d$
P	$(1/K)(T/D)$		
PI	$(0.9/K)(T/D)$	3.3D	
PID	$(1.2/K)(T/D)$	2D	0.5D

#### 4.6.2 Calculation of PID controller using Z-N method for the electric heat furnace system

In this study, the PID parameters ( $k_p$ ,  $k_i$ ,  $k_d$ ) are calculated as follow.

The following equation shows the transfer function of an electric heat furnace system that obtained in chapter three is

$$G(s) = \frac{\theta(s)}{H(s)} = \frac{ke^{-Ds}}{Ts+1} = \frac{1e^{-0.2s}}{20s+1} \quad (4.11)$$

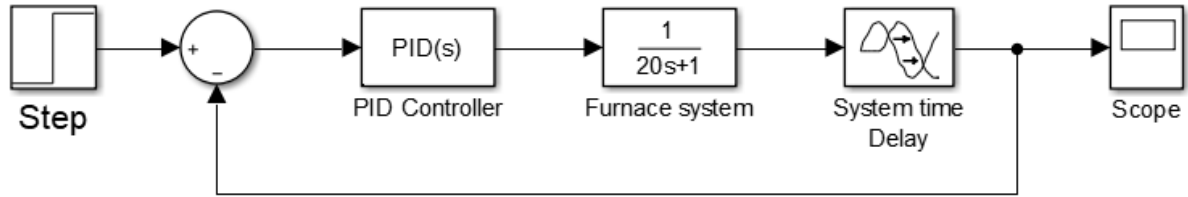


Figure 4.7: Schematic Diagram of conventional PID controller with plant model

From this  $G(s) = \frac{1e^{-0.2s}}{20s+1}$ , the gain ( $K$ ) is 1, the time constant ( $T$ ) is 20, and the delay time ( $D$ ) is 0.2

Hence,  $K_c=K_p = 120$ ,  $\tau_i=2D=0.4$ ,  $\tau_d=0.5D=0.1$

$K_i = \frac{K_p}{\tau_i} = 300$ ,  $K_d=K_p\tau_d = 12$  and, the controller transfer function is therefore

$$G(s) = 120 + \frac{300}{s} + 12s \quad (4.12)$$

## 4.7 Tuning of FOPID controller

Controller tuning of fractional order proportional integral derivative (FOPID) is the process of selecting controller parameters ( $k_p$ ,  $k_i$ ,  $k_d$ ,  $\lambda$  and  $\mu$ ) for the feedback controller. The FOPID controller is done by toolbox known as Fractional-order Modeling and Control (FOMCON) toolbox. The overview and all command of this toolbox are mentioned in [37]. FOPID tuning rules were derived from the fractional PID tuning rules described in [39] for plants.

$$G(s) = \frac{K}{Ts+1} e^{-Ls} \quad (4.13)$$

The parameters of the polynomials involved are given in Table 4.3 [39]. This means that

$$P = -0.0048 + 0.2664L + 0.4982\frac{T}{K} + 0.0232L^2 - 0.0720\left(\frac{T}{K}\right)^2 - 0.0348\frac{LT}{K} \text{ and so on [39].} \quad (4.14)$$

Table 4. 3: lists the variables to utilize for the second set of tuning rules for plants with an S-shaped step response when  $0.1 \leq T/K \leq 50$  and  $L \leq 0.5$ .

	P	I	$\lambda$	D	$\mu$
1	-1.0574	0.6014	1.1851	0.8793	0.2778
L	24.5420	0.4025	-0.3464	-15.0846	-2.1522
T/K	0.3544	0.7921	-0.0492	-0.0771	0.0675
$L^2$	-46.7325	-0.4508	1.7317	28.0388	2.4387
$(T/K)^2$	-0.0021	0.0018	0.0006	-0.0000	-0.0013
LT/K	-0.3106	-1.2050	0.0380	1.6711	0.0021

### 4.7.1 Calculation of FOPID controller for the electric heat furnace system

In this study, the FOPID parameters ( $k_p$ ,  $k_i$ ,  $k_d$ ,  $\lambda$  and  $\mu$ ) are calculated as follow.

The following equation shows the transfer function of an electric heat furnace system that obtained in chapter three is

$$G(s) = \frac{\theta(s)}{H(s)} = \frac{ke^{-Ds}}{Ts+1} = \frac{1e^{-0.2s}}{20s+1} \quad (4.15)$$

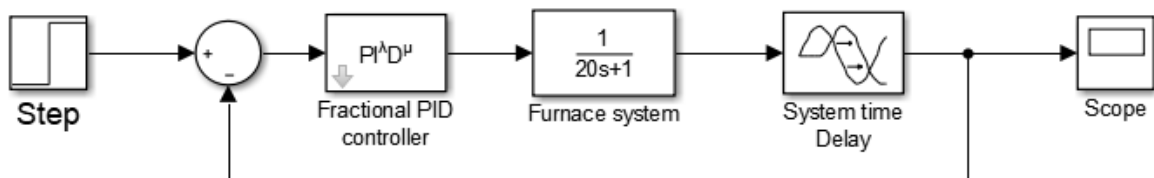


Figure 4.8: Schematic Diagram of FOPID controller with plant model

From this  $G(s) = \frac{1e^{-0.2s}}{20s+1}$ , the gain (K) is 1, the time constant (T) is 20, and the delay time (D) is 0.2

Hence,  $K_p = P = 6.9873$ ,  $K_I = I = 12.4059$ ,  $K_D = D = 4.1264$ ,  $\lambda = 0.5931$ ,  $\mu = 0.7834$

Thus, the controller transfer function is

$$G_{FOPID}(s) = 6.9873 + 12.4059s^{-0.5931} + 4.1264s^{0.7834} \quad (4.16)$$

#### 4.8 Tuning of SPFOPID controller

Controller tuning of Smith Predictor based fractional order proportional integral derivative (SPFOPID) is the process of selecting controller parameters ( $k_p$ ,  $k_i$ ,  $k_d$ ,  $\lambda$  and  $\mu$ ) for the feedback controller. Here all the work of FOPID controller is done on the Smith predictive structure. The SPFOPID controller is done by toolbox known as fmincon toolbox. The overview and all command of this toolbox are mentioned in [20][41]. SPFOPID tuning were derived from the fractional order PID tuning that described in [20] on smith predictor structure.

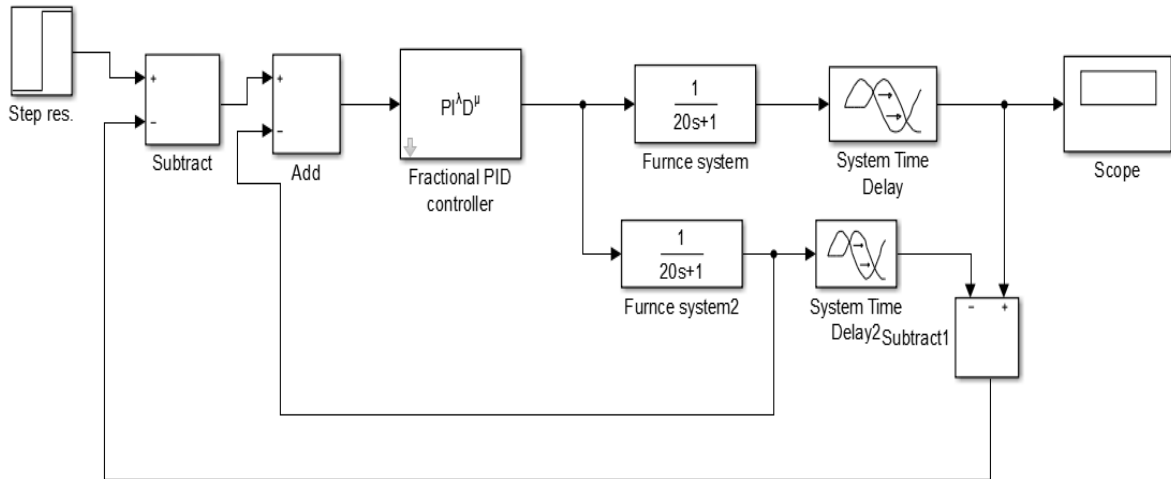


Figure 4.9: Schematic Diagram of SPFOPID controller with plant model

From the  $G(s) = \frac{\theta(s)}{H(s)} = \frac{ke^{-Ds}}{Ts+1} = \frac{1e^{-0.2s}}{20s+1}$ , that obtained in chapter three, the gain (K) is 1, the time constant (T) is 20, and the delay time (D) is 0.2 and taking the gain crossover frequency  $\omega_{gc} = 0.00854 \text{ rad/s}$  and phase margin  $\phi_m = 60^\circ$  [40].

Using the method proposed in [20] [40][41] on the smith predictor structure, the SPFOPID controller parameter is  $K_p = 53.9124$ ,  $K_I = 115.9322$ ,  $K_D = 3.7005$ ,  $\lambda = 0.6769$ ,  $\mu = 0.3886$

Thus, the controller transfer function is

$$G_{SPFOPID}(s) = C(s) = 53.9124 + 115.9322s^{-0.6769} + 3.7005s^{0.3886} \quad (4.17)$$

## 4.9 PSO tuned SPFOPID controller

Here all the work of SPFOPID controller is done by using FOMCON toolbox on MATLAB R2016a. The particle swarm optimization (PSO) algorithm is employed to find the SPFOPID controller's optimal parameters and the theoretical concepts of PSO algorithm is discussed below.

### 4.9.1 Particle swarm optimization (PSO)

Optimization of large groups of particles using an evolutionary computer method inspired by social behavior in the natural world is called particle swarm optimization (PSO) [32].

In computational science, particle swarm optimization (PSO) is a method for optimizing a problem by improving a candidate solution iteratively in terms of a defined quality measure. In PSO, each solution is represented by a "bird" in the search space. The term "particle" is commonly used to describe it. Particles have fitness values and velocities that are evaluated by the fitness function to optimize their motion. As the name suggests, each possible answer in PSO is a "bird" in the search space. It is commonly referred to as a "particle." PSO works best with non-linear issues.

The system starts off with a pool of potential solutions for the random selection problem. In this context, a "particle" refers to any and all potential answers. Each atom has its own history and moves at some unpredictable rate as it explores the problem domain. Each particle is led by its fitness equivalent to its previous best position (Pbest). Different particles in the swarm have different Pbests, and the particle with the highest fitness is called the global best (Gbest). At each time step, the PSO technique uses a randomly weighted acceleration to push each "particle" closer to its Pbest and Gbest positions [33].

The PSO method uses the following equations to determine how each particle in the swarm's speed and location change:

$$v_{id}^{k+1} = Wv_{id}^k + c_1r_1(pbest_{id}^k - x_{id}^k) + c_2r_2^k(gbest_{id}^k - x_{id}^k) \quad (4.18)$$

$$x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \quad (4.19)$$

Where

$v_{id}^{k+1}$  and  $x_{id}^k$  shows the speed and location of the  $i$ th particle (out of  $n$  particles) in the  $k$ th iteration at the  $d$ -dimensional scale (out of  $D$  dimensions).

For each iteration, we keep track of the best local position (i.e. group's best) of the  $i$ th particle (out of  $n$  particles) in the  $d$ -dimension (out of  $D$  dimensions) and the best global position (i.e. group's best) of the  $i$ th particle (out of  $n$  particles) in the  $d$ -dimension (out of  $D$  dimensions), denoted by  $P_{bestid}^k$  and  $X_{id}^k$ , respectively.

The particle has a certain amount of inertia due to its previous position, denoted by  $W$ .

$c_1$  and  $c_2$  indicate the acceleration constant

$r_1^k$  and  $r_2^k$  represent random numbers in the range of  $[0, 1]$ .

#### **4.9.2 Global Best PSO**

The global best PSO (gbest PSO) is a method in which the best-fit particle in the entire swarm influences the position of each particle.

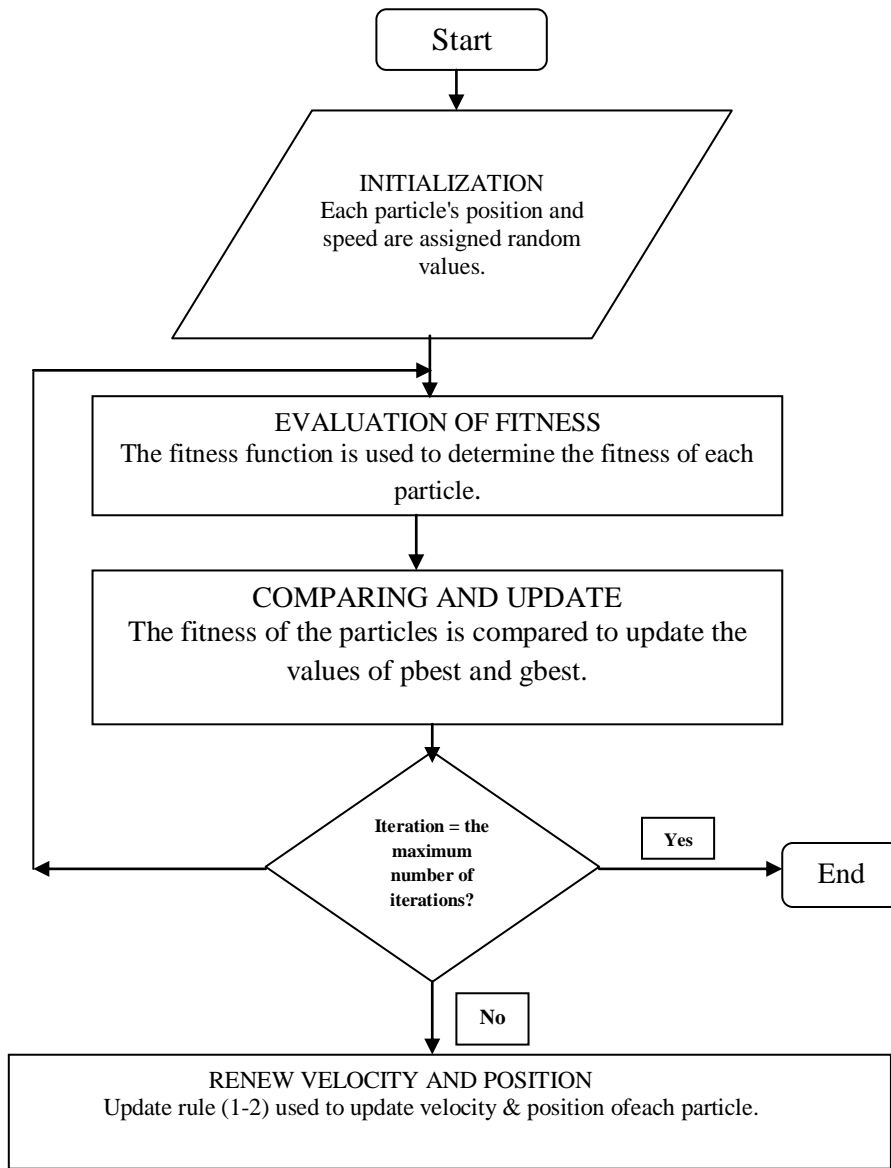


Figure 4.10: Flow chart on evolution of PSO algorithm

### 4.9.3 Parameters of PSO algorithms

Table 4. 4: Parameters of PSO algorithms

Parameters	PSO
Number of Iteration	100
Number of search genis/number of birds	50
$c_1$ acceleration constant 1	1.5
$c_2$ acceleration constant 2	2
W inertia	1
Dimension	3

### 4.9.4 Boundary value of parameters $K_p$ , $K_i$ , $K_d$ , $\lambda$ and $\mu$

Table 4. 5: Boundary value of parameters  $K_p$ ,  $K_i$ ,  $K_d$ ,  $\lambda$  and  $\mu$

$K_p$	0 to 120
$K_i$	0 to 300
$K_d$	0 to 12
$\lambda$	0 to 1
$\mu$	0 to 1

### 4.9.5 Formulation of objective function

#### 4.9.5.1 Integral of time weighted square error (ITSE)

The integral of the time weighted square error [ITSE] is defined as, where the time weighting 't' is employed since the initial error for a step response is always big, and it is sensible to weigh this error less in most set point scenarios. One of the most common criteria for reducing system error and determining the appropriate PID gain values for a particular system response is integral time square error.

$$ITSE = \int_0^{\infty} e^2(t) dt \quad (4.20)$$

# CHAPTER FIVE

## SIMULATION RESULTS AND DISCUSSION

### 5.1 Introduction

In this chapter, the conventional PID, fractional order PID (FOPID), smith predictor based fractional order PID (SPFOPID) and PSO tuned smith predictor based fractional order PID (PSO-SPFOPID) controllers for the temperature control of the electric heat furnace systems is constructed and investigated their performance. The performance of the conventional PID, FOPID, SPFOPID and PSO-SPFOPID controllers are analyzed using graphical and numerical results obtained from the simulation studies on MATLAB R2016a.

### 5.2 Temperature control of electric heat furnace system

#### 5.2.1 Open loop response of electric heat furnace system with time delay

Figure 5.1 shows the Simulink diagram for obtaining the open-loop response of the electric heat furnace system. The open-loop step response of the electric heat furnace system is shown in figure 5.2. From this figure, the response has strictly increased, this means the output response does not get settled for desired temperature value of the electric furnace system. This increasing temperature value has an excessive influence on the product quality. So, the closed-loop feedback system with a proper controller is necessary to maintain the desired set point and reach the steady-state value with less settling time and minimum percentage overshoot.

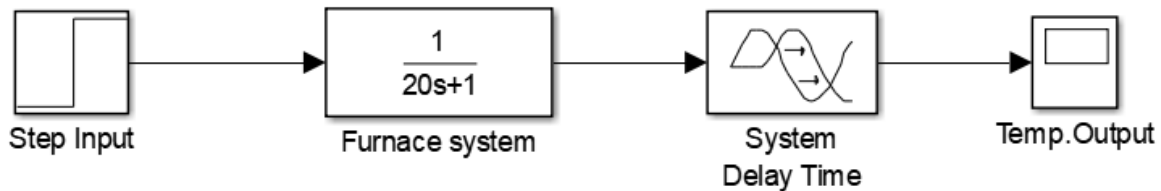


Figure 5. 1: Simulink diagram of open loop response of electric heat furnace system

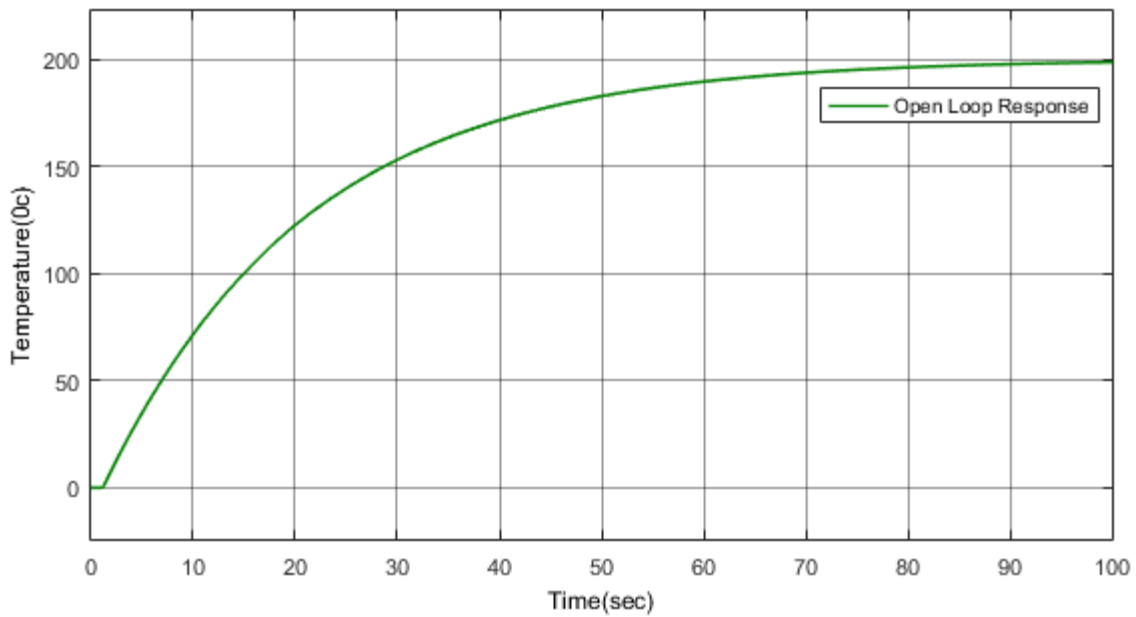


Figure 5. 2: Graphical of open loop response of electric heat furnace system

### 5.3 Temperature control of an electric furnace system using a conventional PID controller

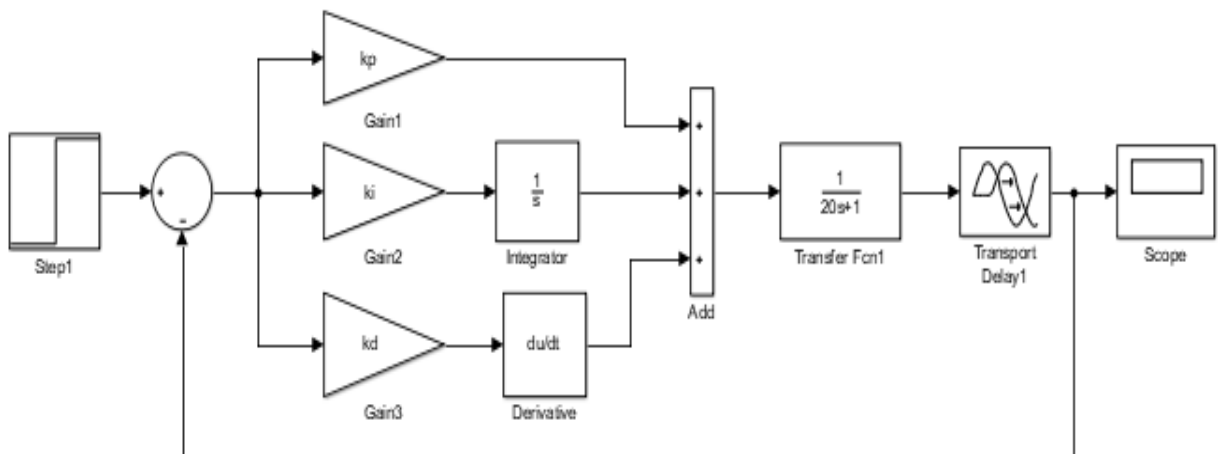


Figure 5. 3: Simulink diagram of electric heat furnace system using conventional PID controller

Table 5. 1: Performance measure, Time response specification and controller parameters of conventional PID controller

Controller	Conventional PID
$K_p$	120
$K_i$	300
$K_d$	12
Rise time (Tr) in sec	0.1730
Settling time (Ts) in sec	19.9497
% Peak overshoot (% Mp)	71.1446

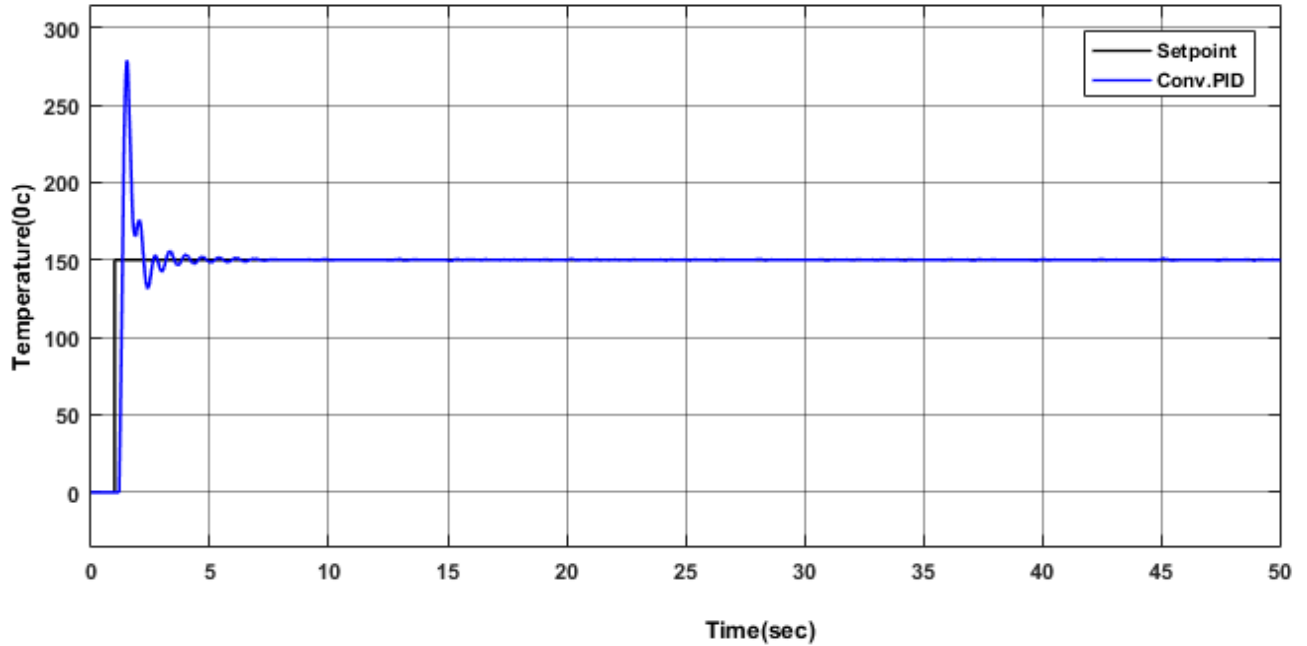


Figure 5. 4: Output response of the temperature control of an electric furnace system using a traditional PID controller

### 5.3.1 Discussion of Temperature control of an electric furnace system using a conventional PID controller

Here, the electric heat furnace system is controlled by a conventional PID controller. The Simulink diagram for a conventional PID Controller used to regulate the temperature of an electric heating furnace is shown in Figure 5.3. In section 4.5.2 of Chapter 4, the Ziegler-Nichols tuning method is used to calculate the parameters of conventional PID controllers.

Table 5.1 details the parameters of the classic PID controller as well as its performance measure and time response specifications. Table 5.1 and figure 5.4 shows that the electric heat furnace system's closed-loop response has a high oscillation and peak overshoot of 71.1446% and takes a long time (19.9497sec) to reach the set point. As a result, the performance of the traditional PID controller is not satisfactory and further improvement is needed.

### 5.4 Temperature control of an electric furnace system using a FOPID controller

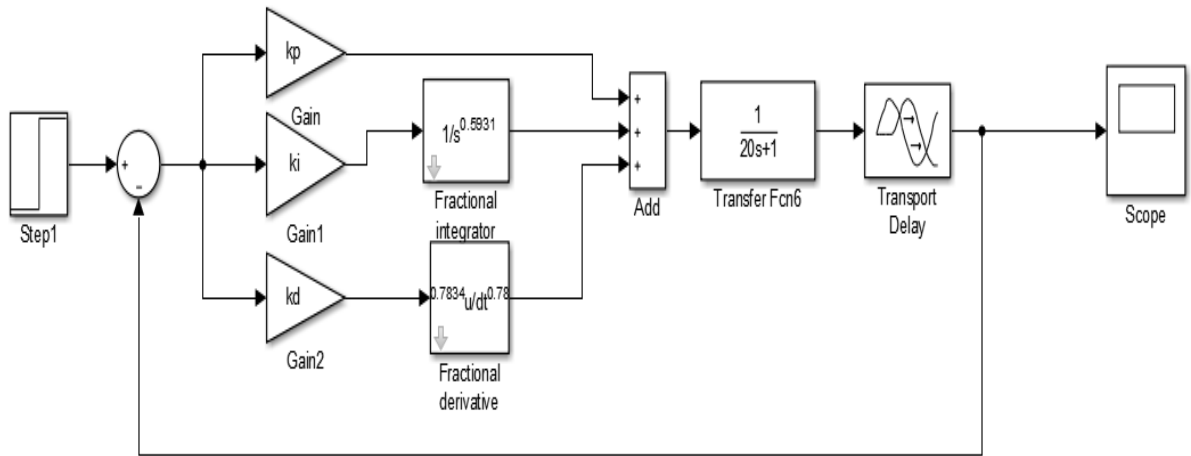


Figure 5. 5: Simulink diagram of the FOPID controller-based temperature control for electric heat furnace systems

Table 5. 2: Performance measure, Time response specification and controller parameters of conventional PID controller and FOPID controller

Controller	Conventional PID controller	FOPID controller
$K_p$	120	6.9873
$K_i$	300	12.4059
$K_d$	12	4.1264
$\lambda$		0.5931
$\mu$		0.7834
Rise time (Tr) in sec	0.1730	1.4912
Settling time (Ts) in sec	19.9497	7.8006
% Peak overshoot (% Mp)	71.1446	18.3924

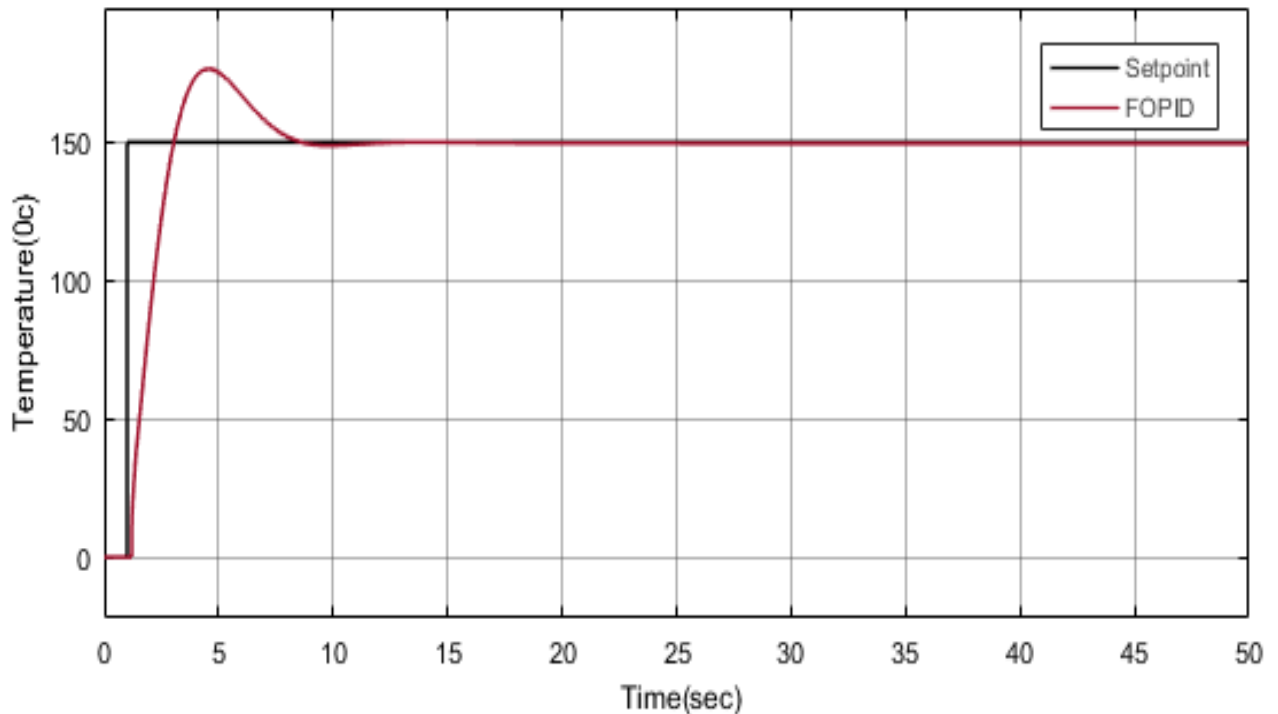


Figure 5. 6: Output response of temperature control of an electric furnace system using FOPID controller

#### 5.4.1 Discussion of Temperature control of an electric furnace system using a FOPID controller

In this section the fractional order proportional integral derivative (FOPID) controller is employed to control the electric heat furnace system. Figure 5.5 displays the Simulink diagram for the temperature control of the electric heat furnace system using a FOPID Controller. In this section, the parameters of the FOPID controllers are calculated in chapter 4, section 4.6.1. The performance measure, time response specifications, and controller parameters of the conventional PID controller and FOPID controller is listed in Table 5.2. Table 5.2 and figure 5.6 shows that the FOPID controller tuned performs well with less settling time (7.8006 sec) and percentage peak overshoot (18.3924%). The performance of the FOPID controller is better than that of the traditional PID controller, as shown in Table 5.2 and Figure 5.6.

## 5.5 Temperature control of an electric furnace system using a SPFOPID controller

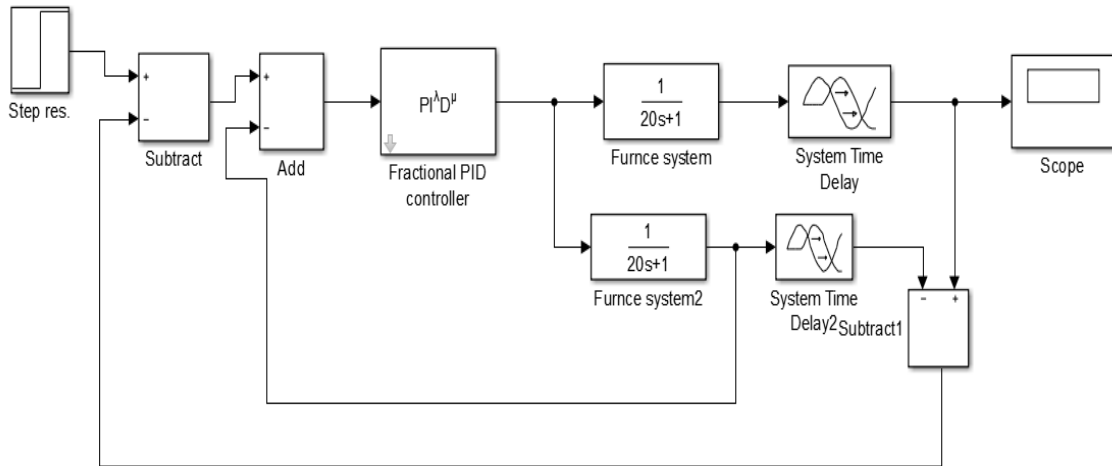


Figure 5. 7: Simulink diagram of SPFOPID controller temperature control for electric heat furnace system

Table 5. 3: Performance measure, Time response specification and controller parameters of FOPID controller and SPFOPID controller

Controller	FOPID controller	SPFOPID controller
$K_p$	6.9873	53.9124
$K_i$	12.4059	115.9322
$K_d$	4.1264	3.7005
$\lambda$	0.5931	0.6769
$\mu$	0.7834	0.3886
Rise time (Tr) in sec	1.4912	0.3595
Settling time (Ts) in sec	7.8006	2.9906
% Peak overshoot (% Mp)	18.3924	10.0851

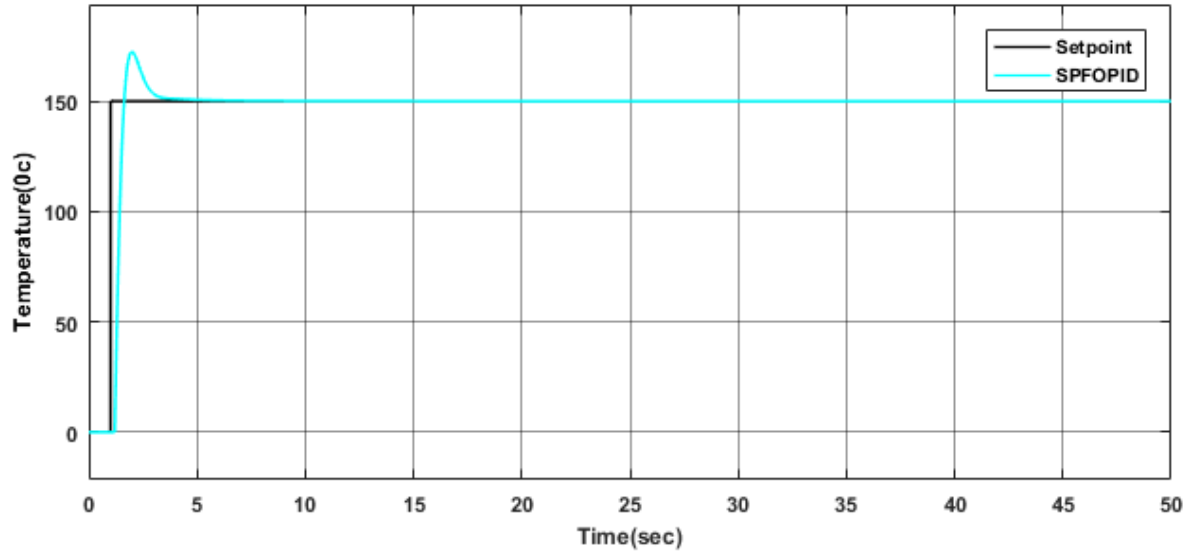


Figure 5. 8: Output response of temperature control of an electric furnace system using SPFOPID controller

### 5.5.1 Discussion of Temperature control of an electric furnace system using a SPFOPID controller

In this section the smith predictor based fractional order proportional integral derivative (SPFOPID) controller is employed to control the electric heat furnace system. Figure 5.7 displays the Simulink diagram for the temperature control of the electric heat furnace system using a SPFOPID Controller. In this section, the parameters of the SPFOPID controllers are obtained in chapter 4, section 4.7. The performance measure, time response specifications, and controller parameters of the FOPID controller and SPFOPID controller is listed in Table 5.3. Table 5.3 and figure 5.8 shows that the SPFOPID controller tuned performs well with less settling time (2.9906 sec) and percentage peak overshoot (10.0851%). The performance of the SPFOPID controller is better than that of the FOPID controller, as shown in Table 5.3 and Figure 5.8.

## 5.6 PSO-tuned SPFOPID controller temperature control for electric heat furnace system

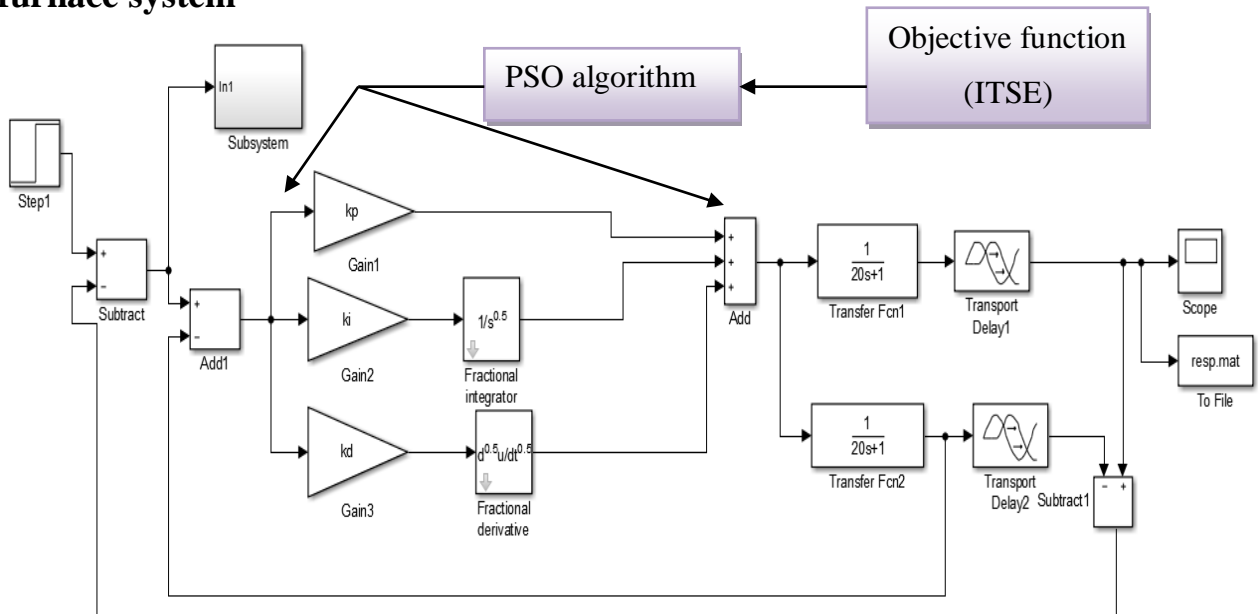


Figure 5. 9: Simulink diagram of PSO-tuned SPFOPID controller temperature control for electric heat furnace system

Table 5. 4: Performance measure, Time response specification and controller parameters of the PSO tuned SPFOPID controller for ten runs

Runs	$K_p$	$K_i$	$K_d$	$\lambda$	$\mu$	Rise time (Tr) in sec	Settling time (Ts) in sec	% Peak overshoot (% Mp)	Objective function ITSE	Converged at(iteration number)
Run 1	47.4931	87.0100	0.8390	0.1974	0.3959	0.3586	1.7284	0.4546	452.4535	35
Run 2	69.2970	181.0200	3.6982	0.0290	0.6013	0.2633	1.8852	3.5814	452.4544	100
Run 3	53.1713	129.5959	3.7082	0.3758	0.6332	0.3579	1.7090	0.7426	452.4612	59
Run 4	80.3994	150.5812	3.7045	0.5208	0.3351	0.2768	1.8063	2.0938	452.4535	54
Run 5	70.8940	159.2362	4.7833	0.3760	0.3326	0.2847	1.8318	2.2196	451.2332	47
Run 6	52.1506	151.8182	3.7199	0.2872	0.3337	0.3268	1.6533	1.7590	452.4724	91
Run 7	58.8468	155.3100	3.7121	0.5405	0.3999	0.3087	1.8342	2.0802	452.4649	17
Run 8	54.1027	116.4323	3.7010	0.6768	0.3893	0.3769	1.7444	0.3235	452.4550	73
Run 9	54.7586	199.4983	3.6714	0.7444	0.5156	0.2651	1.9129	4.7509	452.4403	58
Run 10	58.0261	162.9134	4.9922	0.5202	0.7891	0.3032	1.8479	2.2195	451.3507	61

Table 5. 5: Best value of the Performance measure, Time response specification and controller parameters of PSO tuned SPFOPID controller with SPFOPID controller

Controller	SPFOPID controller	PSO tuned SPFOPID controller
$K_p$	53.9124	47.4931
$K_i$	115.9322	87.0100
$K_d$	3.7005	0.8390
$\lambda$	0.6769	0.1974
$\mu$	0.3886	0.3959
Rise time (Tr) in sec	0.3595	0.3586
Settling time (Ts) in sec	2.9906	1.7284
% Peak overshoot (% Mp)	10.0851	0.4546
Objective function ITSE:		452.4535
Converged at (iteration no)		35

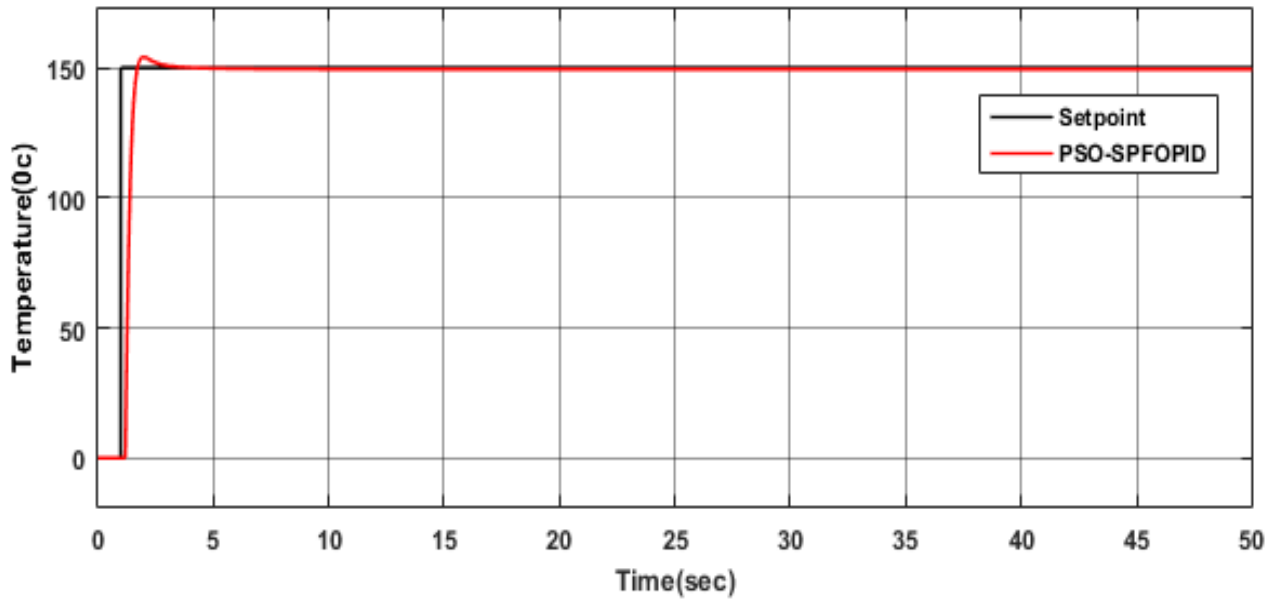


Figure 5. 10: Output response of temperature control of electric heat furnace system using PSO tuned SPFOPID

### 5.6.1 Discussion of Temperature control of an electric furnace system using PSO tuned SPFOPID controller

This section discusses the PSO-tuned smith predictor-based fractional order proportional integral derivative (PSO-SPFOPID) controller for an electric heat furnace. The Simulink diagram for the PSO-tuned SPFOPID controller, which is used to regulate the temperature of the electric heat furnace system, is shown in Figure 5.9. Here, the PSO algorithm is used to determine values for the SPFOPID controller's parameters. In table 5.5, we can see the PSO tuned SPFOPID controllers' performance measure, time response requirements, and controller settings. Table 5.5 and figure 5.10 demonstrate the superior performance of the SPFOPID controller tuned with the PSO algorithm and the objective function ITSE, which has a shorter settling time (1.7284s) and a lower peak overshoot percentage (0.4546%).

## 5.7 Performance comparison of conventional PID, FOPID, SPFOPID controller and PSO tuned SPFOPID controller for the control of electric heat furnace

Table 5. 6: Performance measure, Time response specification and controller parameters of conventional PID controller, FOPID controller, SPFOPID controller and PSO tuned SPFOPID controller

Controller	Conventional PID controller	FOPID controller	SPFOPID controller	PSO tuned SPFOPID controller
$K_p$	120	6.9873	53.9124	47.4931
$K_i$	300	12.4059	115.9322	87.0100
$K_d$	12	4.1264	3.7005	0.8390
$\lambda$		0.5931	0.6769	0.1974
$\mu$		0.7834	0.3886	0.3959
Rise time (Tr) in sec	0.1730	1.4912	0.3595	0.3586
Settling time (Ts) in sec	19.9497	7.8006	2.9906	1.7284
% Peak overshoot (% Mp)	71.1446	18.3924	10.0851	0.4546
Objective function ITSE:				452.4535
Converged at (iteration no)				35

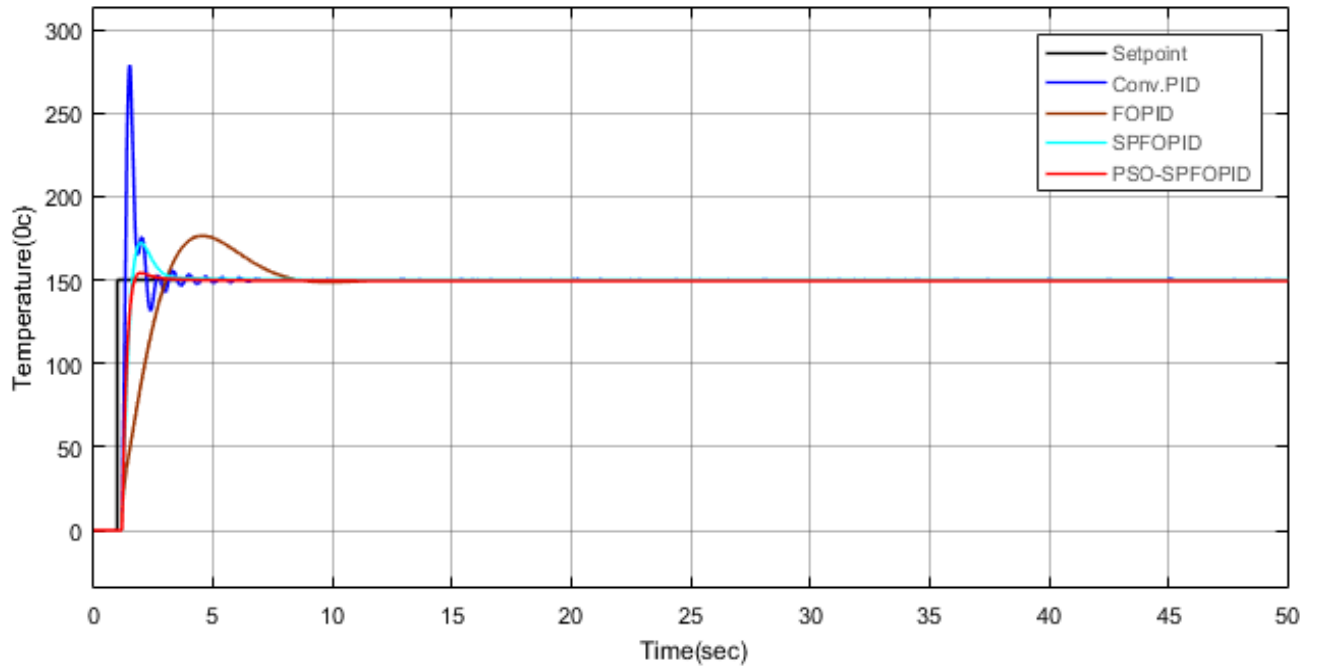


Figure 5. 11: Output response of temperature control of an electric furnace system using a traditional PID controller, FOPID controller, SPFOPIID controller and PSO tuned SPFOPIID

### 5.7.1 Discussion of Performance comparison of conventional PID, FOPID, SPFOPIID controller and PSO tuned SPFOPIID controller for the control of electric heat furnace

In this section the Performance of conventional PID, FOPID, SPFOPIID controller and PSO tuned SPFOPIID controller is compared to control the electric heat furnace system. Here, the performance measure, time response specifications, and controller parameters of the conventional PID, FOPID, SPFOPIID controller and PSO tuned SPFOPIID controller are listed in table 5.6. From table 5.6 and figure 5.11 the SPFOPIID controller tuned using the PSO algorithm with objective function ITSE performs well with less settling time (1.7284sec) and %peak overshoot (0.4546%). That means the PSO tuned SPFOPIID controller performs better than the conventional PID controller, FOPID controller and SPFOPIID controller. Thus, the best result is obtained when the PSO-SPFOPIID is selected.

# **CHAPTER SIX**

## **CONCLUSION AND FUTURE SCOPE**

### **6.1 Conclusion**

In this thesis work, the performance of the PSO tuned SPFOPID controller is compared with the SPFOPID controller, fractional order PID controller and conventional PID controller for the temperature control of the electric heat furnace system. The PSO optimization algorithm is employed for the tuning of SPFOPID controller parameters. From the graphical and numerical results, the PSO tuned SPFOPID controller performed less percentage overshoot (0.4546%) and less settling time (1.7284sec) and rise time (0.3586sec). This indicates that the overshoot and settling times are decreased, by 95.4924% and 42.2056%, respectively, compared to SPFOPID controllers, by 97.5283% and 77.8427%, respectively, compared to FOPID controllers and by 99.3610% and 91.3362%, respectively, compared to conventional PID controllers. Accordingly, it can be concluded that the SPFOPID controller tuned using the PSO algorithm with the objective function of the Integral of Time Square Error performs well to overcome the high percentage overshoot, long settling time, and low clarity.

### **6.2 Recommendation for the future work**

In this thesis work, a Smith Predictor based Fractional Order PID controller with Particle Swarm Optimization algorithm is used to properly design and simulate the temperature regulation of the electric heat furnace system using the MATLAB/Simulink software. The obtained result of the system response is the best as required. Therefore, for future development, this study work of the temperature control of an electric heat furnace system by Smith Predictor based Fractional Order PID controller with Particle Swarm Optimization algorithm may be expanded by including disturbance rejection.

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## APPENDIXES

```
%% Tuning of SP-FOPID Controller Using Particle Swarm Optimization
%
% Copyright (c) 2015, Yarpiz (www.yarpiz.com)
% All rights reserved. Please read the "license.txt" for license terms.
%
% Project Code: YPEA102
% Project Title: Implementation of Particle Swarm Optimization in MATLAB
% Publisher: Yarpiz (www.yarpiz.com)
%
% Developer: S. Mostapha Kalami Heris (Member of Yarpiz Team)
%
% Contact Info: sm.kalami@gmail.com, info@yarpiz.com
%
clc;
clear;
close all;
%% Problem Definition
CostFunction=@tracklsq;    % Cost Function
nVar=5;    % Number of Decision Variables
VarSize=[1 nVar]; % Size of Decision Variables Matrix
VarMin(:,1)=0; % kp
VarMin(:,2)=0; % ki
VarMin(:,3)=0; % kd
VarMin(:,4)=0; % lambda
VarMin(:,5)=0; % mu
VarMax(:,1)=120;    % kp
VarMax(:,2)=300;    % ki
VarMax(:,3)=12;    % kd
VarMax(:,4)=1;    % lambda
VarMax(:,5)=1;    % mu
```

```

% VarMin=-10;      % Lower Bound of Variables
% VarMax= 10;     % Upper Bound of Variables
%
%% PSO Parameters
% MaxIt=1000;    % Maximum Number of Iterations
MaxIt=100;      % Maximum Number of Iterations
nPop=50;       % Population Size (Swarm Size)
% PSO Parameters
w=1;          % Inertia Weight
wdamp=0.99;   % Inertia Weight Damping Ratio
c1=1.5;      % Personal Learning Coefficient
c2=2.0;      % Global Learning Coefficient
% If you would like to use Constriction Coefficients for PSO,
% uncomment the following block and comment the above set of parameters.
% % Constriction Coefficients
% phi1=2.05;
% phi2=2.05;
% phi=phi1+phi2;
% chi=2/(phi-2+sqrt(phi^2-4*phi));
% w=chi;      % Inertia Weight
% wdamp=1;    % Inertia Weight Damping Ratio
% c1=chi*phi1; % Personal Learning Coefficient
% c2=chi*phi2; % Global Learning Coefficient
% Velocity Limits
VelMax=0.1*(VarMax-VarMin);
VelMin=-VelMax;
%% Initialization
empty_particle.Position=[];
empty_particle.Cost=[];
empty_particle.Velocity=[];
empty_particle.Best.Position=[];

```

```

empty_particle.Best.Cost=[];
particle= repmat(empty_particle,nPop,1);
GlobalBest.Cost=inf;
for i=1:nPop
% Initialize Position
particle(i).Position=unifrnd(VarMin,VarMax,VarSize);
% Initialize Velocity
particle(i).Velocity=zeros(VarSize);
% Evaluation
particle(i).Cost=CostFunction(particle(i).Position);
% Update Personal Best
particle(i).Best.Position=particle(i).Position;
particle(i).Best.Cost=particle(i).Cost;
% Update Global Best
if particle(i).Best.Cost<GlobalBest.Cost
GlobalBest=particle(i).Best;

end

end

BestCost=zeros(MaxIt,1);

%% PSO Main Loop

for it=1:MaxIt

for i=1:nPop

% Update Velocity
particle(i).Velocity = w*particle(i).Velocity ...

```

```

+c1*rand(VarSize).*(particle(i).Best.Position-particle(i).Position) ...
+c2*rand(VarSize).*(GlobalBest.Position-particle(i).Position);

% Apply Velocity Limits
particle(i).Velocity = max(particle(i).Velocity, VelMin);
particle(i).Velocity = min(particle(i).Velocity, VelMax);

% Update Position
particle(i).Position = particle(i).Position + particle(i).Velocity;

% Velocity Mirror Effect
IsOutside=(particle(i).Position<VarMin | particle(i).Position>VarMax);
particle(i).Velocity(IsOutside)=-particle(i).Velocity(IsOutside);

% Apply Position Limits
particle(i).Position = max(particle(i).Position, VarMin);
particle(i).Position = min(particle(i).Position, VarMax);

% Evaluation
particle(i).Cost = CostFunction(particle(i).Position);

% Update Personal Best
if particle(i).Cost<particle(i).Best.Cost
particle(i).Best.Position=particle(i).Position;
particle(i).Best.Cost=particle(i).Cost;
% Update Global Best
if particle(i).Best.Cost<GlobalBest.Cost
GlobalBest=particle(i).Best;

end
end

```

```

end
BestCost(it)=GlobalBest.Cost;
disp(['Iteration ' num2str(it) ': Best Cost = ' num2str(BestCost(it))]);
w=w*wdamp;

```

```

end
BestSol = GlobalBest
%% Results
figure;
%plot(BestCost,'LineWidth',2);
semilogy(BestCost,'LineWidth',2);
xlabel('Iteration');
ylabel('Best Cost');
grid on;
fpidbest=BestSol.Position;
tracklsq(fpidbest)
kp = fpidbest(:,1)
ki =fpidbest(:,2)
kd =fpidbest(:,3)
lambda=fpidbest(:,4)
mu =fpidbest(:,5)

```

```

function F = tracklsq(fpid)
% Track the output of optsim to a signal of 1
%     global err
% Variables a1 and a2 are shared with RUNTRACKLSQ
kp=fpid(1);
ki=fpid(2);
kd=fpid(3);
lamda=fpid(4);

```

```

miu=fpid(5);
sprintf('The value of interation Kp= %3.0f,Ki=%3.0f', fpid(1),fpid(2),fpid(3),fpid(4),fpid(5));
% Compute function value
simopt = simset('solver','ode45','SrcWorkspace','Current','DstWorkspace','Current'); %
Initialize sim options
[yout] = sim('mokerSPFOPID',[0 10],simopt);
%
%      %*****
ITSE=sum(tse);
% ISE= max(ise);
load resp.mat
resp=resp';
Timeresp=stepinfo(resp(:,2),resp(:,1))
OS=Timeresp.Overshoot;
Ts=Timeresp.SettlingTime;
if OS <10 && Ts<2.99 % Constraints
F=ITSE % Penalty
else F=ITSE+10e11
end

```